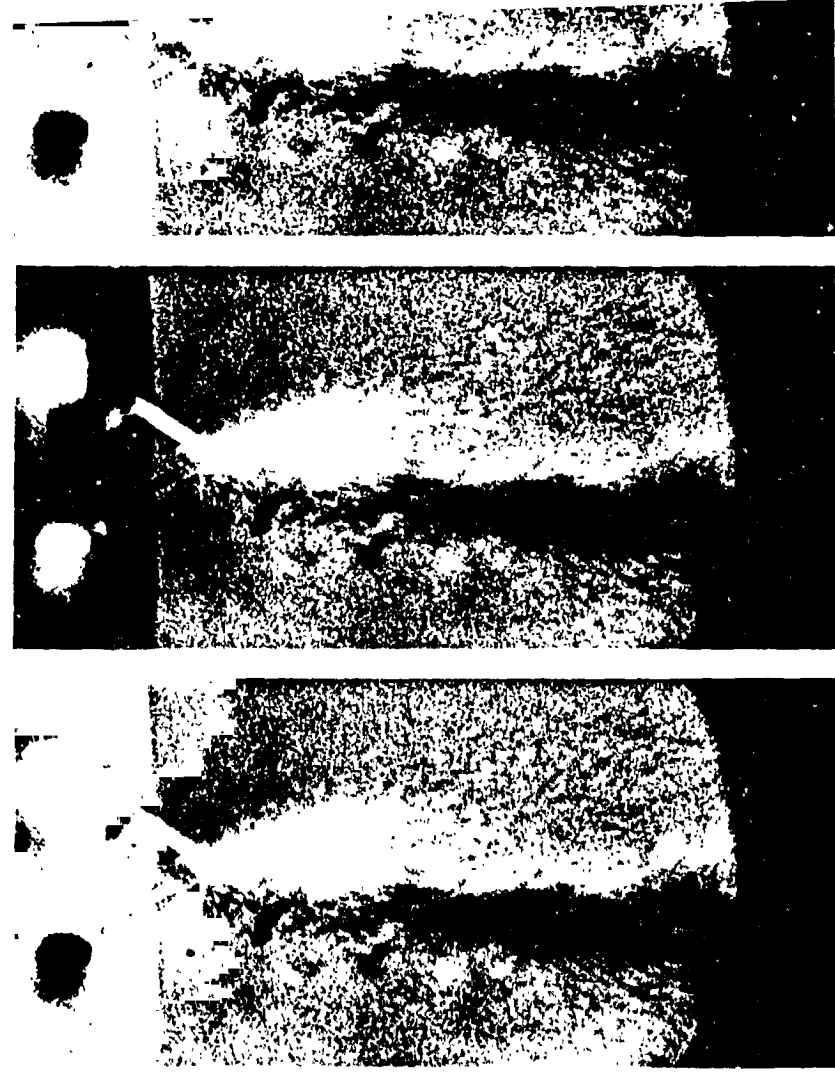# High Performance N2O4/AMINE Elements "BLOWAPART"

Final Report

March 1979

N79-27324

(NASA-CR-160273) HIGH PERFORMANCE
N2O4/AMINE ELEMENTS BLOWAPART Final Report
(Aerojet Liquid Rocket Co.) 171 P
HC A08/MF A01   CSCL 20I   Unclas
                                         G3/28   29209

Contract NAS 9-14186

Prepared By:

B. R. Lawver

NASA JOHNSON SPACE CENTER

ORIGINAL CONTAINS
COLOR ILLUSTRATIONS

AEROJET
LIQUID ROCKET
COMPANY

HIGH PERFORMANCE

N_2O_4/AMINE ELEMENTS - "BLOWAPART"

Contract NAS 9-14186

Final Report 14186-DRL-5

March 1979

Prepared by:

B. R. Lawver

Prepared for:

NASA-Johnson Space Center
Houston, Texas

FOREWORD

This final report describes analytical and experimental work conducted to identify the mechanisms governing Reactive Stream Separation (RSS) and to develop techniques for predicting its occurrence. RSS is a combustion induced phenomenon that results in striation of hypergolic propellant oxidizer and fuel sprays fans. This reduced intra-element mixing (compared to the well-mixed distribution developed in a non-reacting cold flow case) can influence thrust chamber performance, heat transfer, and stability. The activity was performed by Aerojet Liquid Rocket Company on Contract NAS 9-14186, under the direction of Merlyn Lausten, NASA/JSC Project Manager. Aerojet personnel included L. B. Bassham, Program Manager, D. L. Kors, Project Manager and B. R. Lawver, Project Engineer. J. W. Salmon also served as ALRC Program Manager, commencing in January of 1978. The following individuals also contributed significantly to the success of the program:

Paul Lloyd	Test Engineering
Arnold Keller	Test Engineering
Duane Robertson	Test Instrumentation
Cliff Thompson	Combustor Design
Lee Lang	Combustor Design
Gene Hron	Fabrication
Judy Schneider	Data Analysis
Dick Walker	Data Analysis.

iii

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (cont.)

ABSTRACT

An experimental and analytical program was conducted to develop an understanding of the mechanisms controlling hypergolic propellant reactive stream separation (RSS). RSS is a combustion induced phenomenon that results in striation of hypergolic propellant oxidizer and fuel sprays fans. This reduced intra-element mixing (compared to the well-mixed distribution developed in a non-reacting cold flow case) can influence thrust chamber performance, heat transfer, and stability. The program end product was development of design criteria for coping with RSS to allow the design of high performing, stable injectors. RSS mechanisms were identified using high speed color photography to observe reactive stream mixing of single element injectors tested with $N_2O_4/$MMH, $N_2O_4/$A-50, and N_2O_4/N_2H_4 propellants. Three hundred and fifty six tests were run over a chamber pressure range of 60-1000 psia, a fuel temperature range of 55°F-300°F, and a fuel velocity range of 30-200 ft/sec. This wide parametric characterization included modeling of the Space Shuttle Orbital Maneuvering System (OMS) and Reaction Control System (RCS) engine injectors.

Tests were conducted using five different conventionally machined unlike doublet elements and two triplet elements. Also, three platelet elements were tested. Platelet injectors are fabricated by bonding together a stack of thin metal sheets which have etched flow passages. A simulation of the Space Shuttle/RCS engine injector element was included in the unlike doublets and a simulation of the Space Shuttle/OMS engine platelet like-on-like doublet injector element was included in the platelet injectors.

The single element firings were conducted in a specially constructed chamber fitted with quartz windows for photographically viewing the impingement spray field. Analysis of the film identified the occurence of reactive stream separation as evidenced by non-uniform spray fields.

ABSTRACT (cont.)

Distinct regions of mixing and separation were identified and correlated for each of the injectors tested. Color photographs of the combustion phenomena are included. Finally, a working model was developed that correlates RSS as a function of a fuel vaporization rate control parameter.

The most important design criteria derived from this work states that: "the element should be designed to avoid transition between mixed and separatea modes within the engine operational envelope".

I.   SUMMARY

The objective of this program was to develop an understanding of the
mechanisms controlling hypergolic propellant reactive stream separation (RSS).
RSS is a combustion induced phenomenon that results in striation of hyr: ·nlic
propellant oxidizer and fuel sprays fans. This reduced intra-element mixin;
(compared to the well-mixed distribution developed in a non-reacting cold
flow case) can influence thrust chamber performance, heat transfer, and
stability. The program end product was development of design criteria for
coping with RSS to allow the design of high performing stable injectors.
This objective was accomplished through high speed color photography and
analysis of single element injector tests using N_2O_4/MMH, N_2O_4/A-50, and
N_2O_4/N_2H_4 propellants. Three hundred and fifty six tests were run over a
chamber pressure range of 60-1000 psia, a fuel temperature range of 55°F-
300°F, and a fuel velocity range of 30-200 ft/sec. This wide parametric
characterization included modeling of the Space Shuttle Orbital Maneuvering
System (OMS) and Reaction Control System (RCS) engine injectors.

Tests were conducted using five different conventionally machined
unlike doublet injectors and two triplet elements. Also, three platelet
injectors elements were tested. Platelet injectors are fabricated by
bonding together a stack of thin metal sheets which have etched flow passages.
A simulation of the Space Shuttle/RCS injector was included in the unlike
doublets and a simulation of the Space Shuttle/OMS engine platelet like-on-
like doublet injector (T-LOL) was included in the platelet injectors.

The hot firings were conducted in a specially constructed chamber
fitted with quartz windows for photographically viewing the impingement spray
field. Analysis of the film identified the occurrence of reactive stream
separation as evidenced by non-uniform spray fields. Four modes of impingement
were identified from the film; Penetration, Mixing, Mix/Separate and Separation.
Penetration occurs at low injection velocity (less than 50 ft/sec), low fuel
temperatures (below 70°F) and low chamber pressure (less than 100 psia) and

I, Summary (cont.)

is evidenced by "shoot-through" of the fuel and oxidizer. Penetration has
been reported in earlier cold flow work and was also observed on this program
using propellant simulants as well as reactive streams. Penetration is a
consequence of the non-reactive momentum exchange mixing process. Mixing is
observed at moderate injection velocities (50-100 ft/sec), moderate fuel
temperatures (70-90°F) and moderate chamber pressures (100-200 psia). It is
evidenced by a highly uniform spray field which looks similar to a non-reactive
spray field. Mix/Separate occurs at the onset of RSS. It is evidenced by a
slightly non-uniform spray field. Separation is observed at higher injection
velocities (greater than 100 ft/sec), higher fuel temperature (greater than
90°F), and higher chamber pressures (greater than 200 psia). It is evidenced
by highly non-uniform spray fields in which distinct regions of unmixed fuel
and oxidizer exist.

Distinct regions of mixing and separation were identified and corre-
lated for each of the injectors tested. It was found that regimes of RSS
with the coherent stream types of injector (i.e., the unlike doublets and
triplets) are all correlated by the equation;

$$Pc = 4.4 \times 10^8 (REF)^{-1.5} \qquad\qquad \text{Equation (1)}$$

where:

REF = Fuel Orifice Reynolds Number.

Mixing occurs at chamber pressures less than that specified by Equation (1)
and separation occurs at greater chamber pressures. Regimes of RSS with the
self-atomizing platelet types of injectors (i.e., the etched flow passages
create mechanical jet atomization for a single element) are correlated by:

2

I, Summary (cont.)

$$Pc = 1272 \ (REF)^{-0.24} \ (XDT \ \& \ Splash \ Plate) \qquad \text{Equation (2a)}$$

$$Pc = 839 \ (REF)^{-0.24} \ (TLOL). \qquad \text{Equation (2b)}$$

Again mixing occurs at chamber pressures below this value and separation occurs at pressures greater than this. The fuel Reynold's number (REF) successfully correlated RSS because fuel vaporization was identified as the combustion rate limiting mechanism for the propellant combinations tested.

Injector design criteria were developed and are included as Appendix A of this report. The most important design criteria derived from this work states that, "transitions from regimes of mixing to separation and vice-versa should be avoided within the engine operational envelope". If an element can not be made to operate entirely within the mixing regime then it is better to redesign the element such that it operates entirely within the separation regime. The reason for this design approach is to create relatively constant combustion response to allow optimum design of injector/ chamber performance, heat transfer, and stability characteristics. Coherent jet RSS was shown to be a strong function of the operating chamber pressure. The self-atomizing elements tend to operate predominately in the separated mode for most practical applications and are relatively insensitive to chamber pressure change. They are therefore ideal for engines which must operate over wide Pc-MR ranges.

Testing with the Space Shuttle/RCS unlike doublet identified non-reactive off-momentum effects that can also modify spray mixing uniformity with unlike doublets. These results show that elements that are insensitive to momentum changes such as the triplet or pentad are preferable to unlike doublets for engines that must operate over a wide mixture ratio range.

3

II.   INTRODUCTION

The objective of this program was to develop an understanding of the mechanisms controlling hypergolic propellant reactive stream separation (RSS). The program end product was development of design criteria for coping with RSS to allow the design of high performing stable injectors.

Hypergolic earth-storeable N_2O_4/Amine propellants have been historically used for a wide range of liquid propulsion system applications. They are used on the first, second and third stages of the Titan II and Titan III launch vehicle. Also, they have been the near exclusive choice for reaction control and orbital maneuvering systems with low to moderate ΔV requirements (e.g., Apollo and Space Shuttle). These propellants are highly reactive and can experience reactive stream separation (RSS) (i.e., blowapart) which can inhibit intra-element mixing hence reducing the overall spray mixture ratio and mass distribution. Modifications of the spray uniformity can result in altered combustion efficiency, gas-side heat transfer coefficient, and stability. It is imperative that the RSS phenomena be understood so that the designer of today's high efficiency engines can cope with its effects.

Several studies (References 1-17) have been conducted over the past decade in an effort to understand the RSS phenomena, identify operational limits of RSS, and develop design criteria for its avoidance. Several RSS models were postulated but none were able to account for all of the experimental data. Also conflicting data were reported due to problems of definition and problems of experimental limitation.

This study was undertaken to; clarify some of the previous studies; to provide a consistent set of data for the identification of mechanisms responsible for RSS and; to map RSS regimes for a wide range of injector elements including Space Shuttle applications. The injector elements and the range of parameters tested are summarized in Table I. A more detailed data summary is included in Appendix B.

4

TABLE I

SUMMARY OF INJECTOR ELEMENTS AND TEST CONDITIONS

Fuel	Injector* Elements	P_c (psia)	V_f (ft/sec)	T_f (°F)	MR
MMH	1,2,3,4,5 6,7,8,9,10,11	40-1000	30-220	50-300	1.4-3.2
A-50	1	90-1000	50-160	60-85	1.6-1.7
N_2H_4	1,4,5,8	60-460	30-175	60-90	1.4-2.0

*Injector Element Code

1. Rounded Inlet Unlike Doublet, $D_f = 0.020$ Long Impingement (.160 in.)

2. Rounded Inlet Unlike Doublet, $D_f = 0.020$ Short Impingement (.040 in.)

3. Small F-O-F Triplet $D_f = 0.020$

4. Large F-O-F Triplet $D_f = 0.029$

5. Small Sharp Edged Unlike Doublet, $D_f = 0.020$

6. Large Sharp Edged Unlike Doublet, $D_f = 0.030$

7. Space Shuttle/RCS Unlike Doublet, $D_f = 0.023$

8. Space Shuttle/RCS Unlike Doublet, Offset Impingement, $D_f = 0.023$

9. Space Shuttle/OMS TLOL Platelet Injector, $D_f = 0.028$

10. XDT Platelet, $D_f = 0.021$

11. Splashplate Platelet, $D_f = 0.021$

5

II, Introduction (cont.)

Fuel vaporization rate controlled combustion was identified as the RSS governing mechanism and was used to develop an RSS model. RSS operating limits were defined for all of the injector elements listed in Table I.

Injector design criteria were developed and are included as Appendix A of this report. The primary element design criteria states that the elements should be designed to avoid transitions between mixed and separated modes within the engine operating Pc-MR range. The element design criteria provides the necessary data required to meet this goal.

The technology developed on this program has been used to aid the development of the Space Shuttle Orbital Manuevering System (SS/OMS) engine, the development of an advanced injector during the Improved Transtage Injector Program (ITIP), and to characterize the Space Shuttle Reaction Control System (SS/RCS) engine injector element. The study results are also applicable to future systems, particularly those utilizing earth storable hypergolic propellants.

III.   TECHNICAL APPROACH

The objective of this program was to develop an understanding of the mechanisms controlling hypergolic propellant RSS. Design criteria for coping with RSS to allow the design of high performing stable injectors would be developed with that understanding. The approach taken was to clarify some of the previous studies to provide a consistent set of data for the identification of mechanisms responsible for RSS, and to map RSS regimes for a wide range of injector elements that included Space Shuttle engine applications. Clarification of the previous studies was accomplished through an evaluation of the data and RSS models found in the literature. These results were used to initiate an iterative model development/test program as shown in Figure 1.

The program was incrementally funded as indicated in Figure 2. Spreading the funding over a four year period has proven to be a cost effective way to develop this technology. Sufficient time was available to thoroughly assess the data, apply the results to engine development problems, and get feedback for program direction, as illustrated in Figure 1. This work was especially instrumental in the successful development of the Space Shuttle/ OMS engine platelet injector.

The inter-relationship of each task toward development of the program final vaporization controlled RSS model is shown in Figure 3. The Task I objectives were to; critique all existing models relating to RSS, review and summarize all associated RSS data, and formulate updated RSS model based on existing data. The results of this work are documented in Reference 18.

The Task II objective was to prepare a detailed program plan, i.e., to formulate a detailed method of approach to be taken for model testing and verification in subsequent tasks. This work is documented in Reference 19.
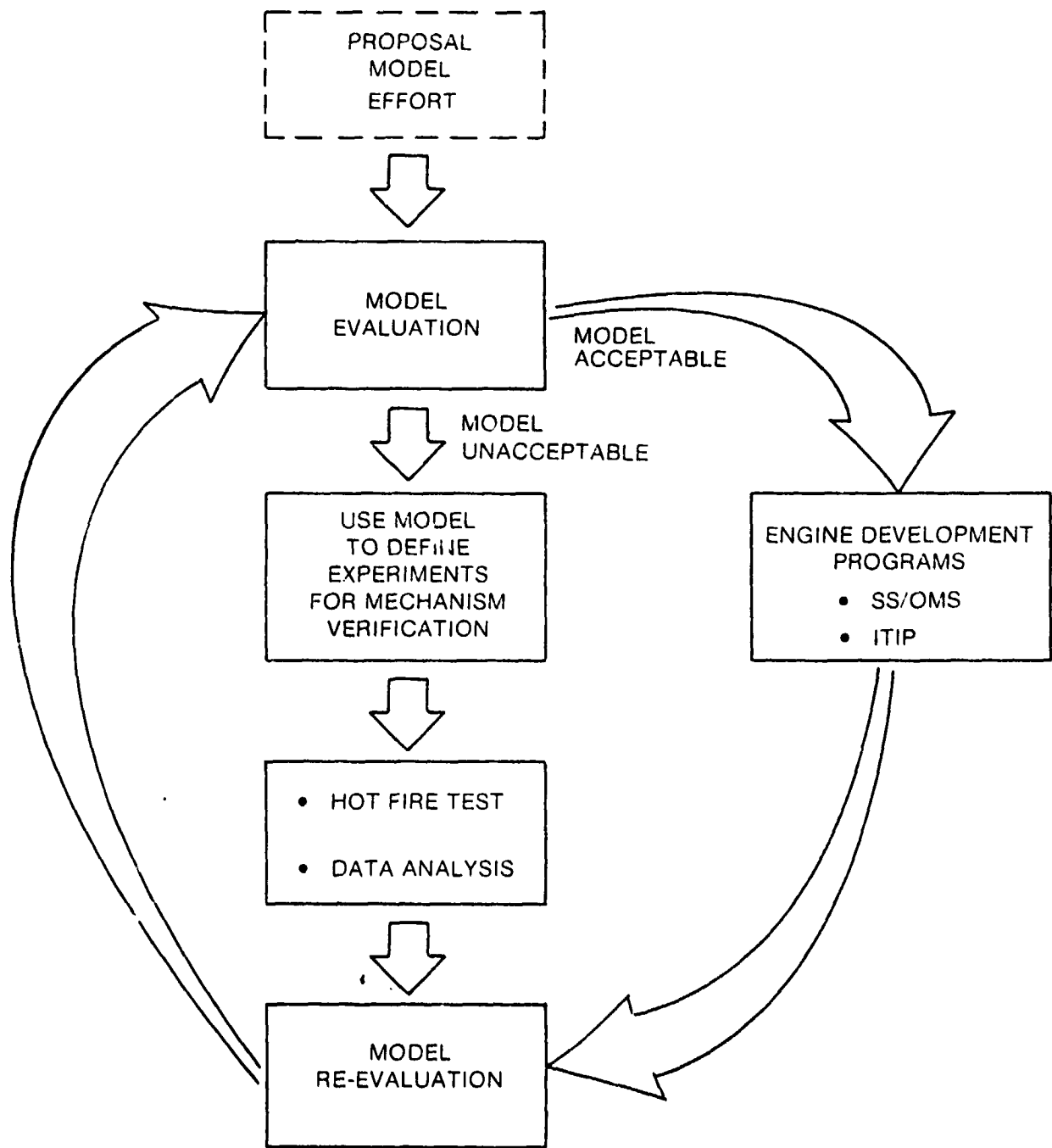
Figure 1. RSS Model Development Approach

TASK DESCRIPTION	'74	'75	'76	'77	'78
I. MODEL & DATA REVIEW					
II. PROGRAM PLAN PREPARATION					
III. DEFINITION OF GOVERNING MECHANISMS	△———	△			
IV. VERIFICATION OF GOVERNING MECHANISMS		△———	△		
V. MODEL DEVELOPMENT					
VI. ELEMENT DESIGN AND FAB			△———	△	
VII. EVALUATION OF FLIGHT TYPE ELEMENTS				△———	△
VIII. INJECTOR ELEMENT DESIGN CRITERIA					

FUNDING SCHEDULE

$50K

$50K

$25K

$100K

———
$225K
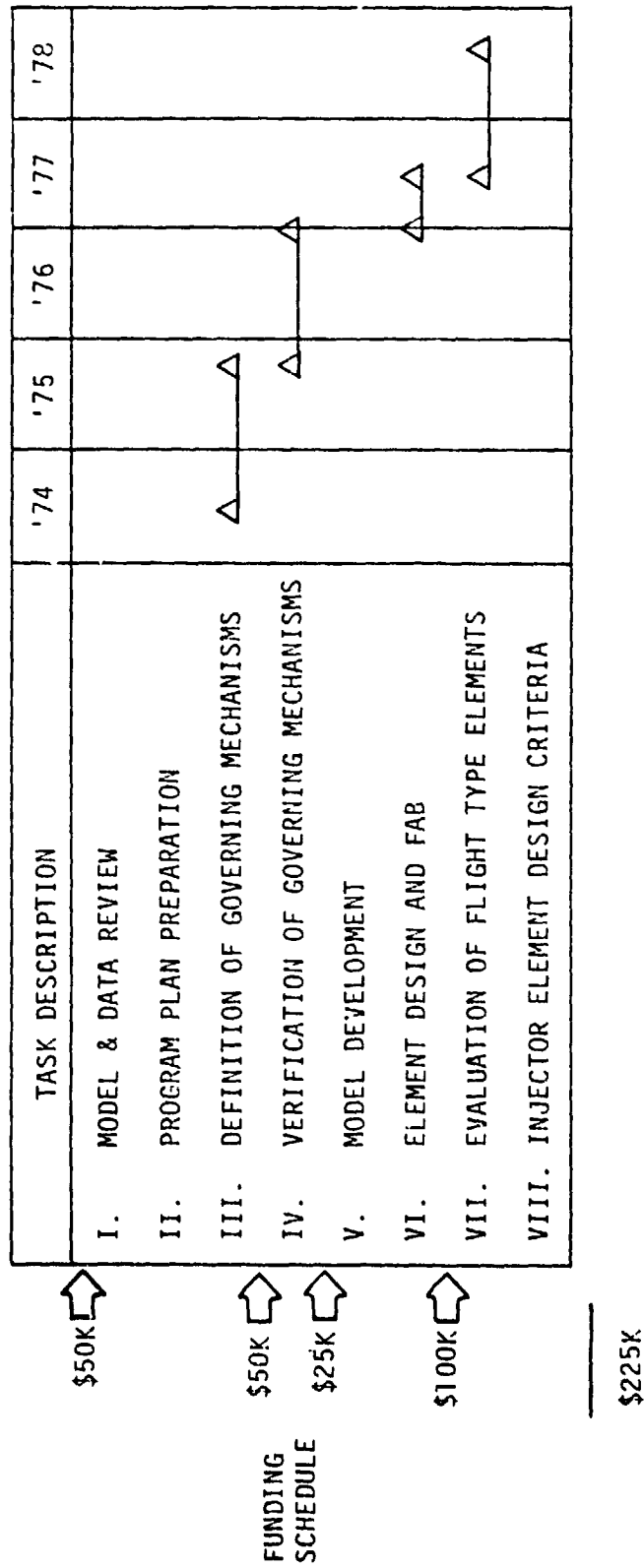
Figure 2.   Blowapart Technology Program Approach
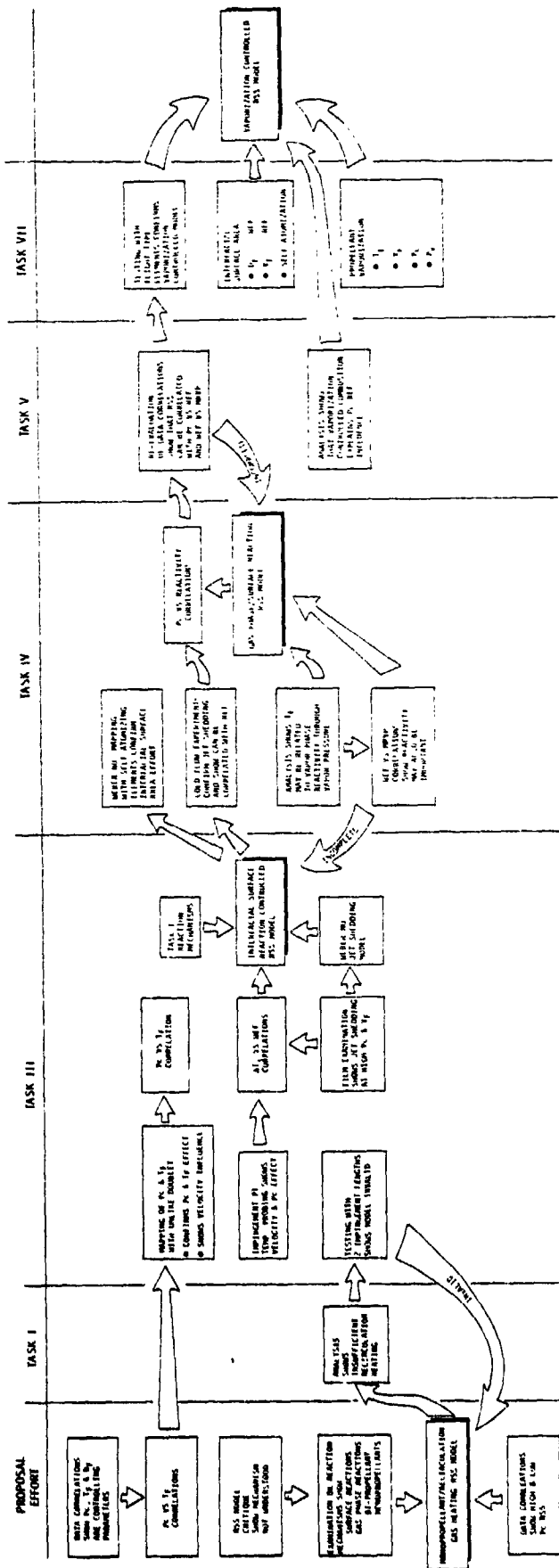
Figure 3. RSS Model Development Chronology

III, Technical Approach (cont.)

The Task III objectives were to define the mechanisms governing RSS, establish limits for RSS and to define appropriate models. The work included; design, fabrication and testing of two single element unlike doublet injectors, incorporation of high speed photographic techniques for visual propellant stream characterization, and correlation of RSS with various independent test variables. The results of the Task III work are documented in Reference 20.

The Task IV objectives were to; establish operating limits for RSS for other injector types, and verify mechanisms governing RSS and the appropriate physical models resulting from the Task III work. The Task IV effort included the design, fabrication and testing of triplet and self-atomizing platelet injectors. The term "self-atomizing" as used here means that a single propellant provides the atomization, either by self impingement or by impingement with a surface. This work is documented in Reference 21.

The objective of Task V was to review all available reactive stream separation data and develop a more comprehensive RSS model. This model effort was directed toward definition of mixed and separated zones which can be related to injector element design and operating parameters. The output of this task was used to select operating conditions to be tested in Task VII, the final model verification tests.

The objective of Task VI was to design and fabricate two flight type injectors. A sharp-edged unlike doublet and the Space Shuttle/RCS unlike doublet element were selected. Each of the injectors incorporated independently manifolded elements so that two different single element designs were built within each of the injector bodies. In addition, a previously designed and fabricated platelet like doublet element (TLOL), which dupli-

III, Technical Approach (cont.)

cates the SS/OMS engine core element design was made available for Task VII
testing. The results of Task V and VI are documented in Reference 22.

The Task VII objectives were to define regimes of RSS for the flight
type injector elements fabricated in Task VI. Testing included the sharp-
edged unlike doublet, the Space Shuttle/RCS unlike doublet, the Space
Shuttle/OMS platelet TLOL, and the rounded inlet unlike doublet. Both
MMH and N_2H_4 fuels were tested. The results of this work are included
herein.

The Task VIII objective was to prepare an element design criteria
for coping with the effects of RSS. The design criteria are included as
Appendix A.

IV. RESULTS AND CONCLUSIONS

A. RESULTS

Regimes of RSS were identified for the following coherent
jet and self-atomizing impingement type injector elements using high
speed color photography;

Coherent Jet
Elements
- Unlike Doublet
  - Rounded Inlet Long L/D (L/D = 12)
  - Sharp Edged Short L/D (L/D = 5)
  - Space Shuttle/RCS (L/D = 10)
- Fuel-Oxidizer-Fuel Triplet

Self-Atomizing
Elements
- X-Doublet Platelet
- Splash Plate Platelet
- Space Shuttle/OMS Like-on-Like Doublet Platelet

Vaporization controlled combustion has been identified as the
mechanism controlling RSS with both coherent and self-atomizing injector
elements. Data correlations for coherent jet elements made on the basis
of a vaporization controlled RSS model show that regimes of RSS are
correlated with chamber pressure and the fuel orifice Reynolds Number as
shown in Figure 4. The fuel orifice Reynolds Number correlates RSS because
fuel vaporization is combustion rate controlling for the N_2O_4/Amine fuels
propellant combinations. The Reynolds number includes the design
parameters that have a first order influence on vaporizing rate. The chamber
pressure exhibits the strongest influence on RSS, increasing chamber pressure
promotes RSS. Orifice diameter, injection velocity and propellant temperature
effects are correlated with the fuel orifice Reynolds Number. Increasing
anyone of these promotes RSS. Self-atomizing elements experience RSS at
lower pressure and show less of a Reynolds Number dependence than the coherent
jets as shown in Figure 5.

13

CHAMBER PRESSURE, Pc, PSIA

1000

100

10

10^3 10^4 10^5 10^6

FUEL ORIFICE REYNOLDS NUMBER, REF

INJECTOR ELEMENTS	ID NO.	FUELS
ROUNDED INLET UNLIKE DOUBLET	1,2	MMH, A-50, N_2H_4
F-O-F TRIPLET	3,4	MMH
SHARP EDGED UNLIKE DOUBLET	5,6	MMH, N_2H_4
SS/RCS UNLIKE DOUBLET	7,8	MMH

SEP

MIX

$Pc = 4.4 \times 10^8 \ (REF)^{-1.5}$

□   MIX
*   MIX/SEP
+   SEP
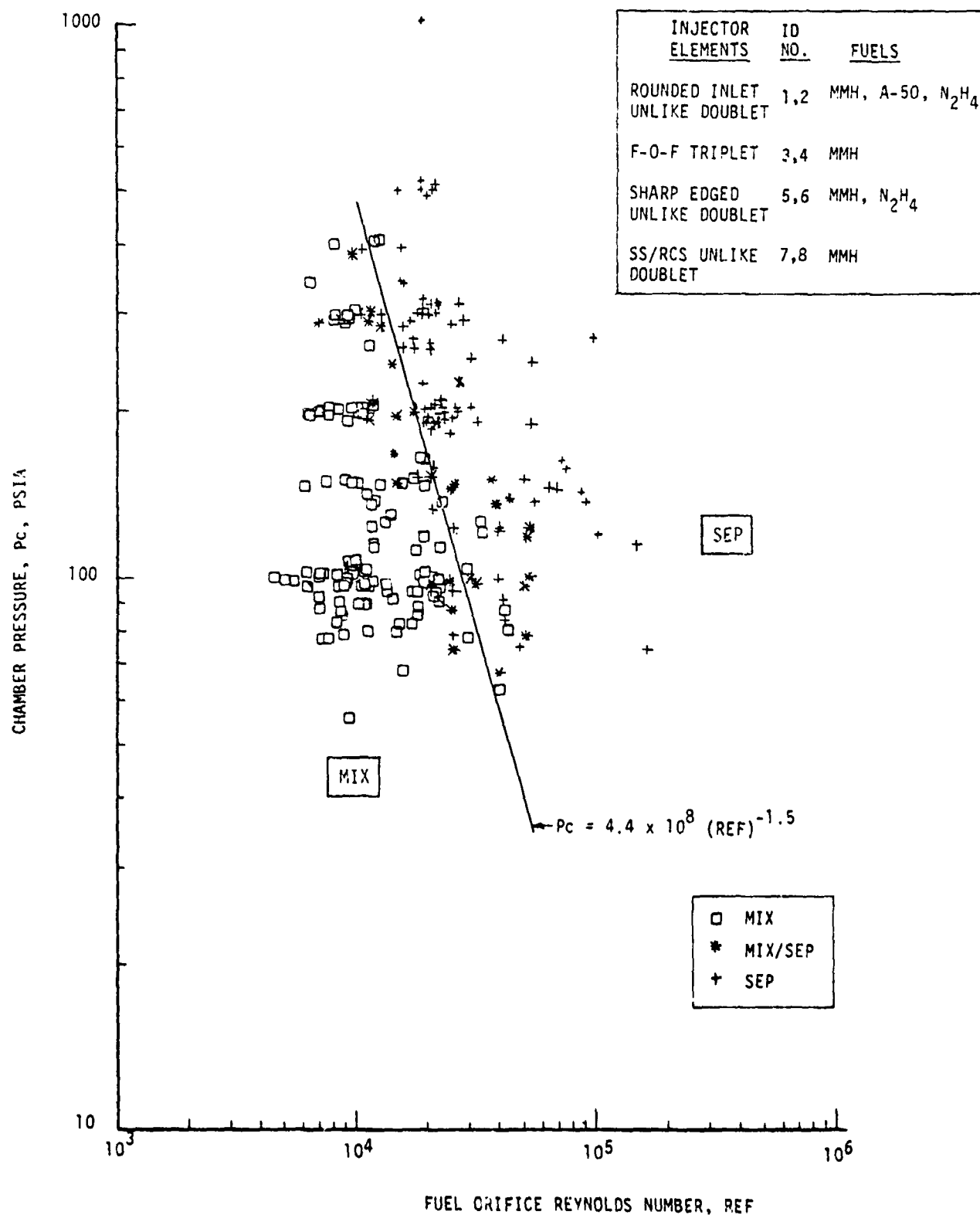
Figure 4.   Vaporization Model Correlates RSS for Coherent
Stream Impingement Injector Elements

14
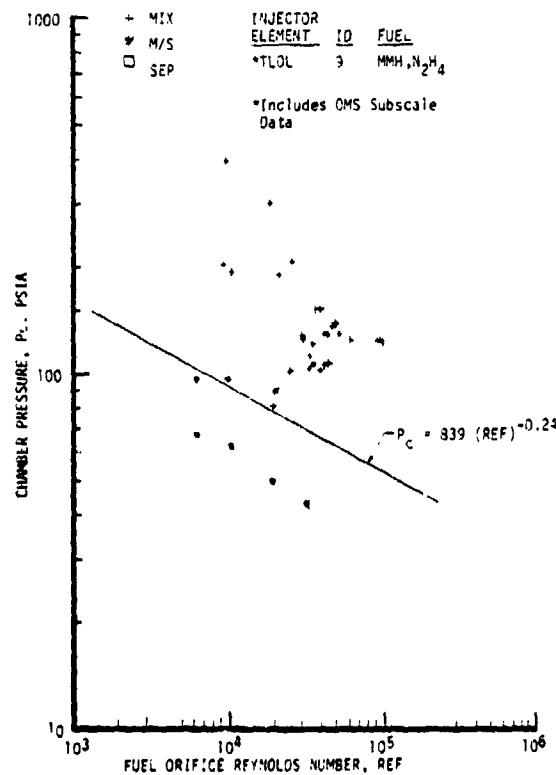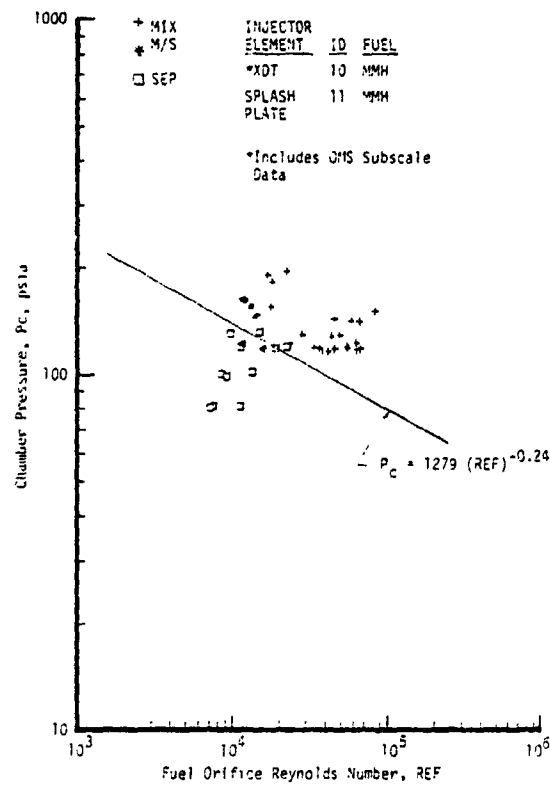
Figure 5.   Vaporization Model Correlates RSS for Self-Atomizing Injector Elements

15

IV, Results and Conclusions (cont)

    B.   CONCLUSIONS

        The following conclusions are drawn from this work.

        1.   The single element hot fire investigation technique has
provided an effective, low-cost approach for understanding the earth-storable
hypergolic propelant combustion process.

        2.   Photographic coverage of single element combustion has been
verified as a valuable process understanding technique.

        3.   RSS is a consequence of vaporization controlled combustion
at the impingement interface.

        4.   RSS regimes are defined by the chamber pressure and fuel
orifice Reynolds Number for a wide range of injector elements.

        5.   Operation in RSS transition regimes should be avoided if
the spray mass and mixture ratio distributions are to be controlled.

        6.   RSS technology has benefited storable engine development.

        7.   Non-hypergolic impingement may experience RSS since vapori-
zation is the controlling mechanism.

V.   APPLICATION OF RESULTS AND RECOMMENDATIONS

A.   APPLICATION OF RESULTS

The application of the results of this program can be grouped
under three headings; 1) development of RSS design criteria and high speed
color photography techniques for hypergolic propellants, 2) application
of these techniques on current hypergolic propellant technology and development
programs, and 3) application of these techniques to advanced systems utilizing
other propellant combinations.

1.   Hypergolic Propellant RSS Models and Techniques

The primary result of this program is the development of
design criteria for coping with RSS experienced with hypergolic N_2O_4/Amine
propellants. These design criteria provide guidelines for the design of
high performing stable injectors. Criteria for both coherent stream and
atomized spray impingement type of injector elements are included. (See
Appendix A).

A secondary but important result of this program is the
development of high speed color photography techniques for observing single
element injector combustion. RSS design criteria could not have been
developed without these techniques. The high speed color photography is
applicable to both single and multiple element injector combustion tests.

2.   Application to Current Programs

These photographic techniques were used on the Acoustic
Cavity Technology for High Performance Injector Program (Ref. 23), Contract
NAS 9-14232, to observe cavity/injector pattern interactions. The under-
standing gained has aided the development of stability prediction models
at the Aerojet Liquid Rocket Company.

V, A Application of Results (cont.)

The technology and techniques developed on this program were used on the Space Shuttle/OMS engine injector development program (Ref. 24) to solve an injector related "resurge" stability problem. A high frequency "resurge" instability persisted despite numerous design modifications. Analysis of OMS and OME technology test results indicated that "resurge" instability involved chamber acoustics, injector hydraulics, and the combustion process. The first order stability influencing parameters were found to be the injector element design, the injector ring manifold and orifice hydraulics and the chamber acoustic cavity configuration.

ALRC combustior stability models were used to evaluate injector designs to predict differences in their stability characteristics. Their predicted stability behavior were then compared to the experimentally known behavior to identify the probable mechanisms and appropriate design parameters which might account for the stability differences. The following parameters were identified as stabilizing influences and consequently selected for element design criteria:

- Element hydraulic inertance
- Unlike impingement height
- Atomization
- Element and pattern mixing rate
- Energy Release Efficiency (ERE) vs chamber length profile.

Understanding of these combustion parameters was accomplished through the use of uni-element and multi-element subscale injectors. Uni-element injector cold flow tests were conducted to characterize the element and spray hydraulics to determine the spray fan geometry, the unlike impingement height, the relative atomization distribution, and the element pressure drop. The more promising uni-element designs were hot fire tested in

18

V, A, Application of Results (cont.)

the photographic chamber designed and fabricated on this program to compare
element spray combustion rates and sensitivity. Hot fire characterization
was achieved through:

     1. Analysis of high speed movies using techniques developed
on this contract to identify the influence of design parameters and operating
conditions on relative spray mixing and "blowapart".

     2. Measurement of C* performance used to quantify spray
mixing influences.

     3. Perturbation of the element sprays with a shock tube
to measure their high frequency combustion pressure response.

     The fundamental understanding of the combustion process
gained from the subscale tests was used to synthesize three fullscale platelet
injector patterns for dynamic combustion stability demonstration. No
evidence of "resurge" instability was encountered on any of the three full
scale platelet injectors. Furthermore, all delivered acceptable performance
and demonstrated that it is not necessary to sacrifice performance to improve
stability characteristics. Good chamber compatibility was also achieved.

     The transverse like-on-like (TLOL) platelet injector element
was selected for the OMS engine as a result of the subscale program. The
spray mass and mixture ratio distributions produced by this element were
found to be insensitive to engine operating point which permits greater
predictability of performance, compatibility and stability. The TLOL
platelet element OMS injector pattern design has in fact demonstrated
good performance, excellent combustion stability and excellent chamber
compatibility. The OMS engine is the first manrated engine to be flight
qualified to the rigid CPIA 247 stability specification.

V, A, Application of Results (cont.)

The Space Shuttle/RCS engine injector element was photo-
graphically characterized over its full chamber pressure/mixture ratio
operating range. This element was observed to be extremely sensitive to
operating condition not only from an RSS standpoint but also from a stream
momentum balance standpoint. These photos have aided understanding of the
SS/RCS engine performance and compatibility.

3. Application to Future Systems

The photographic techniques developed on this program can
be used to establish an understanding of combustion phenomena associated
with any fuels and injectors. The fuel vaporization rate controlled RSS model
developed during the program is currently being extended to hydrocarbon
fuels on the Photographic Combustion Characterization of LOX/Hydrocarbon
Type Propellants Program, Contract NAS 9-15724. This investigation will also
utilize single element photography to gain understanding of combustion
processes.

B. RECOMMENDATIONS

The following recommendations are made on the basis of the
program results.

1. The RSS criteria should be incorporated into the JANNAF
standardized performance computer programs to warn the designer of
operation within RSS regimes.

2. The photographic techniques should be used to define
combustion mechanisms with fuels for prospective new engines.

20

VI. TECHNICAL DISCUSSION

A. EXPERIMENTAL HARDWARE AND TEST SETUP

1. Test Apparatus

The test apparatus consists of a test chamber equipped with transparent viewing ports and removable injectors and nozzles as shown in Figure 6. The test chamber and an unlike doublet injector were designed and fabricated during the Task III effort. Two triplet and two platelet injector elements were designed and fabricated during the Task IV effort. Two sharp-edged unlike doublet elements and two Space Shuttle/RCS unlike doublet elements were designed and fabricated during Task V and VI.

a. Test Chamber

The test chamber was machined from a 4-inch square x 6-inch long block of 304 CRES. The combustion chamber section is 4 inches (10.16 cm) long, to which a 2 in. (5.08 cm) L* spacer is bolted to increase the combustion zone length to 6 inches (15.2 cm). The block was bored to provide a 2.75 inch (6.99 cm) diameter combustion chamber. Four circular quartz windows were provided to facilitate photography and to allow flexibility in photographic lighting of the combustion process. The windows are 1/2 inch (1.27 cm) thick to provide a safety margin for 1000 psia (6.89×10^5 N/m^2) operation. The flat quartz windows are sandwiched between durabula gaskets for cushioning against ignition shocks and uneven loading. A silicon "0" ring provides sealing on the window periphery. Quartz windows are used to provide good propellant compatibility and well defined optical properties.

The chamber was designed to provide an inert gas (GN$_2$) film purge to prevent obscuring the view by propellant spray impingement

KISTLER PORT

FUEL ORIFICES

LONG IMPINGEMENT UNLIKE DOUBLET

NO. 1

SHORT IMPINGEMENT UNLIKE DOUBLET

OXIDIZER ORIFICES

2 INCH DIAMETER

NOZZLE RETAINING RING

COPPER NOZZLE

SINGLE ELEMENT INJECTOR

2" DIA QUARTZ VIEWING PORT 4 PLACES

2.75" DIA

WINDOW RETAINING RING

INJECTOR MOUNTING RING

WINDOW PURGE INLET
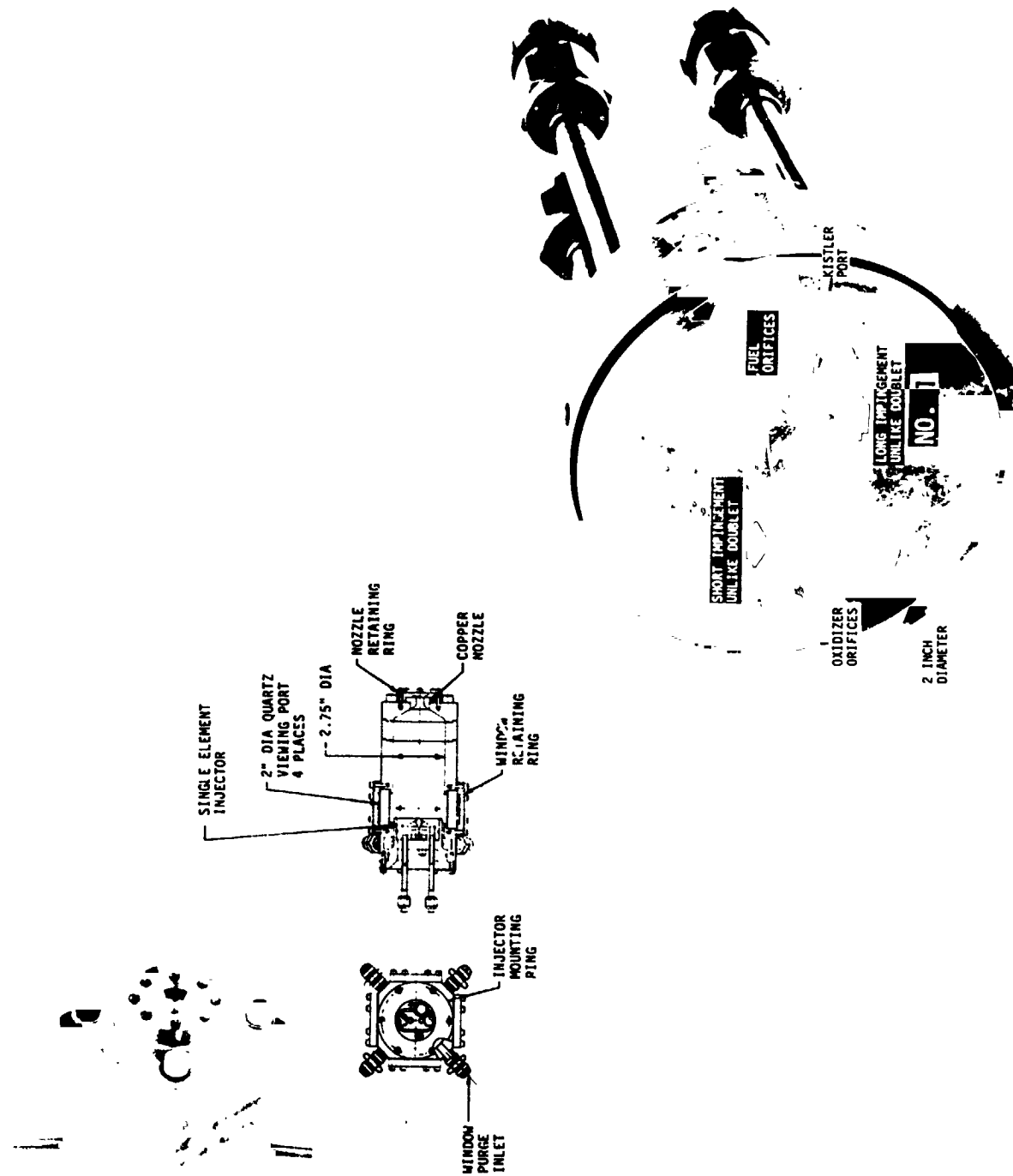
Figure 6. Photographic Test Chamber and Single Element Injector

22

on the windows. The gas purge flow is injected through four inlets into
an annular manifold. The gas is directed from the manifold through an
annular gap and made to flow around the periphery of the chamber wall.
The gas passages were sized such that the GN_2 is injected into the chamber
at 50 ft/sec (15.2 m/sec) at 300 psia (2.07 x 10^6 N/m^2) chamber pressure
to minimize mixing with the propellant spray and combustion gas. Task II
testing showed that the cold GN_2 purge gas causes poor spray field visi-
bility due to the density gradient created between it and the hot combustion
gas. A significant improvement in visibility was made during Task IV by
eliminating the purge gas entirely. All subsequent tests were run without
purge gas.

Provisions was made for mounting both high and low
frequency response pressure transducers and thermocouples. The nozzles
consist of removable copper inserts drilled to provide the desired operating
pressures.

b. Injectors

Four different unlike doublet injectors, two triplet
injectors, and three platelet injectors were tested during the program.
The detailed orifice configurations for each of these injectors are shown
in Figure 7. All but the SS/OMS platelet injector were designed and fabricated
on this program. The SS/OMS injector was obtained from the OMS subscale injector
development program (Reference 24).

(1) Task III Injector

The injector bodies were made in a cylindrical
"piston" shape as shown in Figure 8 to fit into the chamber purge ring
located at the forward end of the chamber. The injector is held in the

23

NO. 1

ROUNDED INLET
UNLIKE DOUBLET ELEMENT,
LONG IMPINGEMENT
LENGTH

NO. 2

ROUNDED INLET UNLIKE DOUBLET
ELEMENT, SHORT IMPINGEMENT
LENGTH

NO. 3

SMALL F-O-F TRIPLET
ELEMENT

NO. 4

LARGE F-O-F TRIPLET
ELEMENT

NO. 5

SMALL SHARP EDGED
INLET UNLIKE DOUBLET
ELEMENT

NO. 6

LARGE SHARP EDGED
INLET UNLIKE DOUBLET
ELEMENT

NO. 7

SPACE SHUTTLE/RCS
UNLIKE DOUBLET ELEMENT

NO. 8

SPACE SHUTTLE/RCS
UNLIKE DOUBLET, ELEMENT
OFFSET IMPINGEMENT

NO. 9

SPACE SHUTTLE/OMS
TLOL CORE PLATELET ELEMENT

NO. 10

XDT PLATELET
ELEMENT

NO. 11

SPLASHPLATE
PLATELET ELEMENT

F - FUEL ORIFICE

0 - OXIDIZER ORIFICE

DIMENSIONS IN
INCHES

Figure 7. Injector Element Orifice Configurations

24
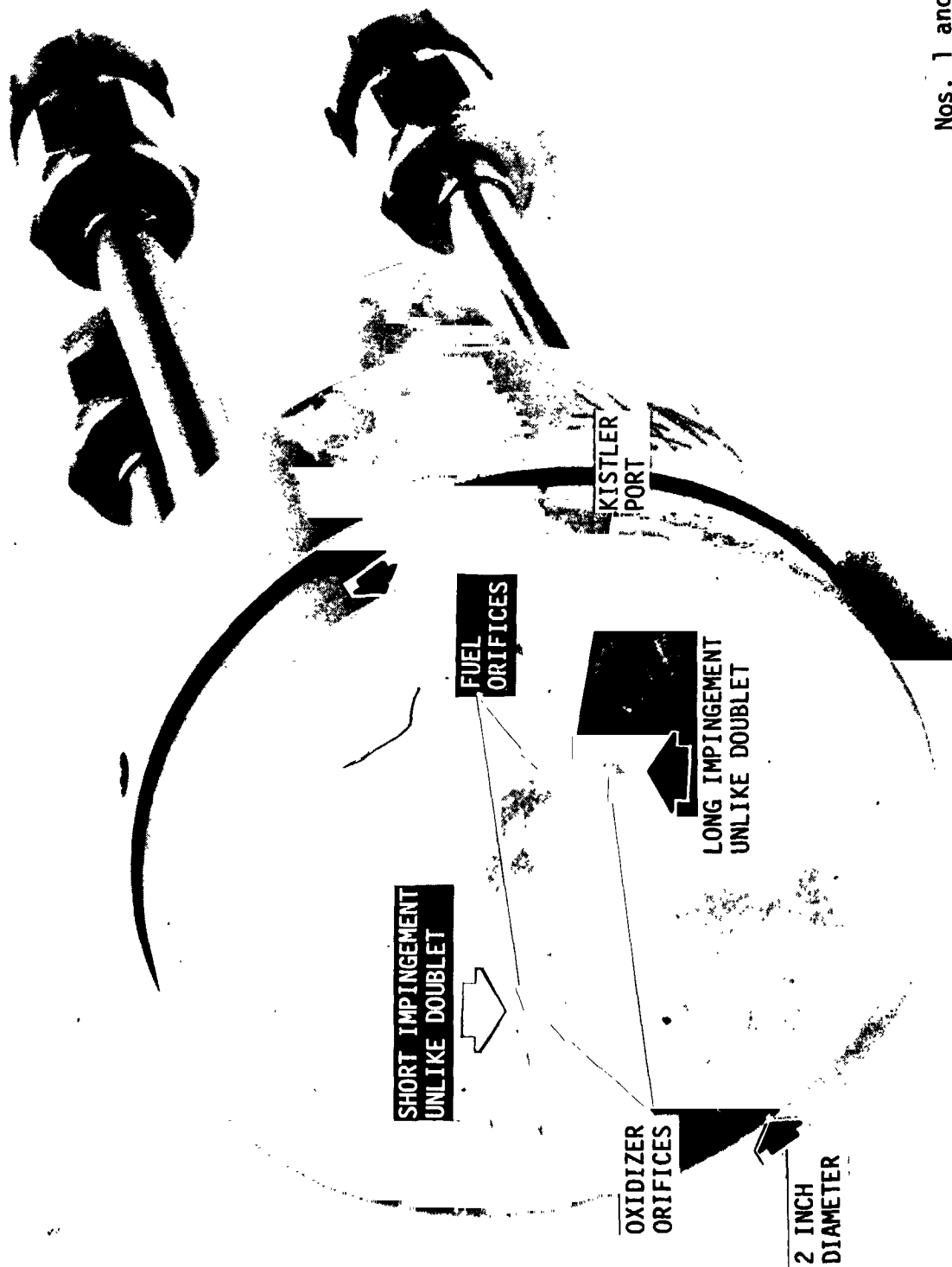
Figure 8. Rounded Inlet Unlike Doublet Injector

Nos. 1 and 2

FUEL ORIFICES

LONG IMPINGEMENT UNLIKE DOUBLET

KISTLER PORT

SHORT IMPINGEMENT UNLIKE DOUBLET

OXIDIZER ORIFICES

2 INCH DIAMETER

VI, A, Experimental Hardware and Test Setup (cont.)

purge ring by allen head screws. A silicon rubber O-ring seals the injec-
tor to the purge ring.

The injector consists of a main body with brazed-
on inlet tubes. The injectors were made of 304 CRES to permit braze
assembly and provide dimensionally stable orifices. Two injector patterns
were incorporated in one body as shown in Figure 6 to reduce fabrication
costs. The Task III rounded inlet unlike doublet element design parameters
are included in Figure 5. The orifice L/D's were made long (24/1) with
rounded inlets to provide controlled hydraulics.

The injector orifices were flow tested prior
to the Task III hot fire testing to measure Kw's and to verify impingement
accuracy. The flow data are discussed in Section VI.C.1. Subsequent cold
flow tests were run during Task IV to characterize the rounded inlet
orifice hydraulics. Results of these tests are also discussed in Section
VI.C.1.

A high frequency response Kistler pressure
transducer mounting port was provided in the long impingement doublet as
shown in Figure 6 to measure impingement point disturbances. This port
was also used to install a high response thermocouple for measuring the
impingement point temperature rise.

(2) Task IV Injectors

The F-O-F triplet element and the self-atomizing
platelet element were selected for test evaluation during Task IV. Two
different triplet injectors were designed to evaluate the influence of
orifice diameter on RSS. The large triplet element has 0.030 inch (.076 cm)
diameter fuel orifices and the small one has 0.020 (.05 cm) inch dia.

VI, A, Experimental Hardware and Test Setup (cont.)

fuel orifices as shown in Figure 9. The orifice design details are shown
in the schematic of Figure 7. Both elements were EDM machined into the
same injector body to reduce fabrication costs. Separate propellant inlets
were provided.

The orifices were designed with short L/D's
and sharp edged inlets to simulate typical rocket injector orifice hydraulics.
The results of a cold flow evaluation of the triplet injectors are discussed
in Section VI.C.1.

The X-doublet and the splashplate self atomizing
platelet elements shown in Figure 10 were selected for test evaluation. Both
elements were photoetched into the same platelet stack to minimize cost.
The platelet stack was bolted to an injector body provided with a single
set of propellant inlets. Manifolding of the desired element was accomp-
lished by rotation of the platelet stack. "O" rings were used to seal the
platelet stack propellant passages to the injector body.

The X-doublet element consists of a parallel
self-atomizing fuel and a parallel self-atomized oxidizer stream placed in
close proximity to one another such that mixing occurs by parallel stream
momentum exchange. Self-atomization is accomplished by self-impingement
within the platelet stack as shown in Figures 10 and 13. The resultant
atomized stream is ejected perpendicularly from the platelet stack. The
splash plate element consists of one self-atomized fuel stream impinging on
one self-atomized oxidizer stream. The self-atomization is produced by imping-
ing the propellant stream against a splash plate as shown in Figure 10.

(3) Task VI Injector

The sharp-edged inlet unlike doublet, the
Space Shuttle/RCS unlike doublet, and the Space Shuttle/OMS platelet

27

Figure 9. F-O-F Triplet Injector

Nos. 3 and 4

FUEL ORIFICES

KISTLER PORT

LARGE TRIPLET

OXIDIZER ORIFICES

SMALL TRIPLET

FUEL ORIFICES

FUEL

OX

PLATELET STACK

INJECTOR BODY

KISTLER PORT

X-DOUBLET No. 10
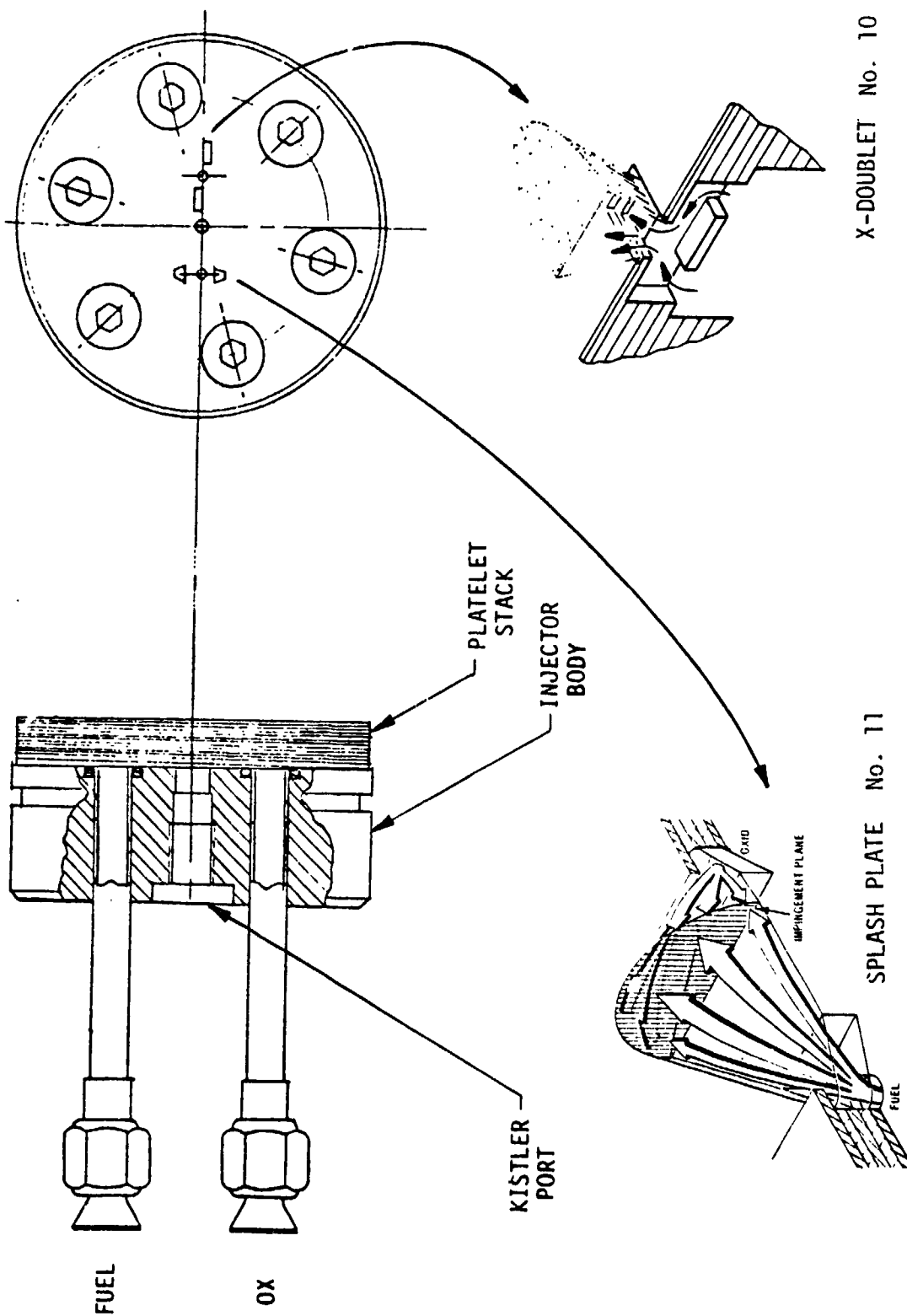
SPLASH PLATE No. 11

Figure 10. XDT and Splash Plate Platelet Injectors

TLOL elements were selected in Task V for testing in Task VII. The sharp-edged inlet unlike doublet injectors are shown in Figure 11. The orifice configurations are shown in Figure 7. The L/D's were selected to be about 4/1 to represent a typical flight configuration. Two fuel orifice diameters were selected, a 0.020 in. diameter and a 0.030 in. diameter, to determine orifice diameter effects. Both elements were EDM'ed into the same injector body to save fabrication costs.

The Space Shuttle/RCS unlike doublet injector is shown in Figure 12. The detailed orifice configuration is shown in Figure 7 Two elements were designed and fabricated to test the effect of impingement. mismatch. One element was made per the design with good centerline impingement. The second element was made with a 0.003 inch impingement mismatch. The results of cold flow of these elements are discussed in Section VI.C.1.

The Space Shuttle/OMS engine platelet Transverse Like On Like (TLOL) injector element is shown in Figure 13. The TLOL element is designed to simulate the spray mixing of a conventional like-on-like injector. The fuel and oxidizer streams are made to impinge on one another to form sprays which are subsequently impinged. The platelet stack contains two elements, the core element and the boundary element which differ only in unlike impingement height. The boundary element has a longer impingement height and lower fan cant angle than the core element. Only the core element was tested on this program.

2. Hot Fire Test Facility Setup

The test apparatus was setup in the ALRC Research Physics Laboratory Test Bay 2 as shown in Figure 14. A schematic of the propellant system used is shown in Figure 15. Propellant (MMH/A-50/N_2H_4/NTO) is stored in 50-gallon, 3000-psi run vessels. Gaseous nitrogen pressurization of these
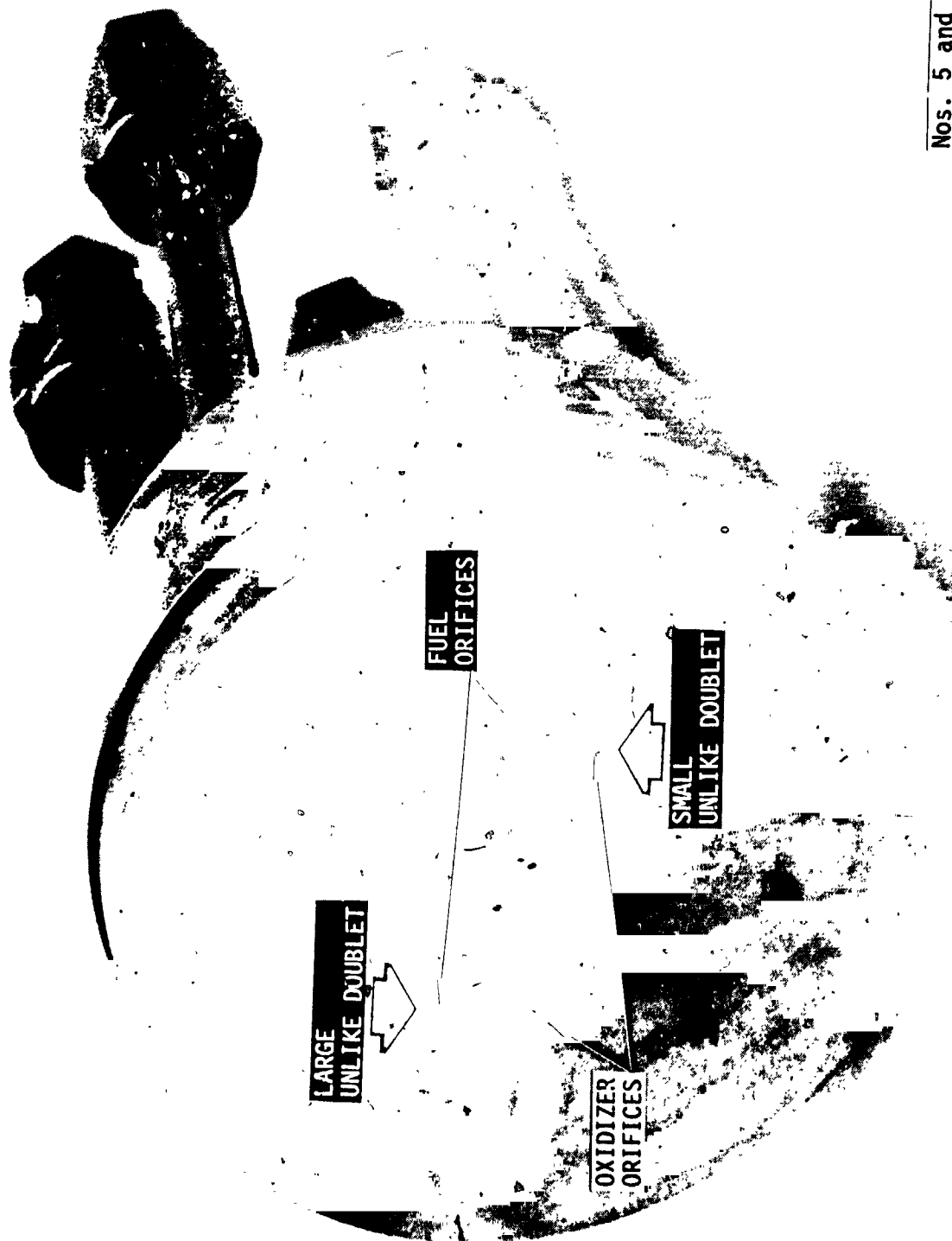
Figure 11. Sharp-edged Inlet Unlike Doublet Injector

LARGE UNLIKE DOUBLET

FUEL ORIFICES

SMALL UNLIKE DOUBLET

OXIDIZER ORIFICES

Nos. 5 and 6

31

Figure 12. Space Shuttle/RCS Unlike Doublet Injector

Nos. 7 and 8

NORMAL
IMPINGEMENT
UNLIKE DOUBLET

OFFSET
IMPINGEMENT
UNLIKE DOUBLET

OXIDIZER
ORIFICES

FUEL
ORIFICES
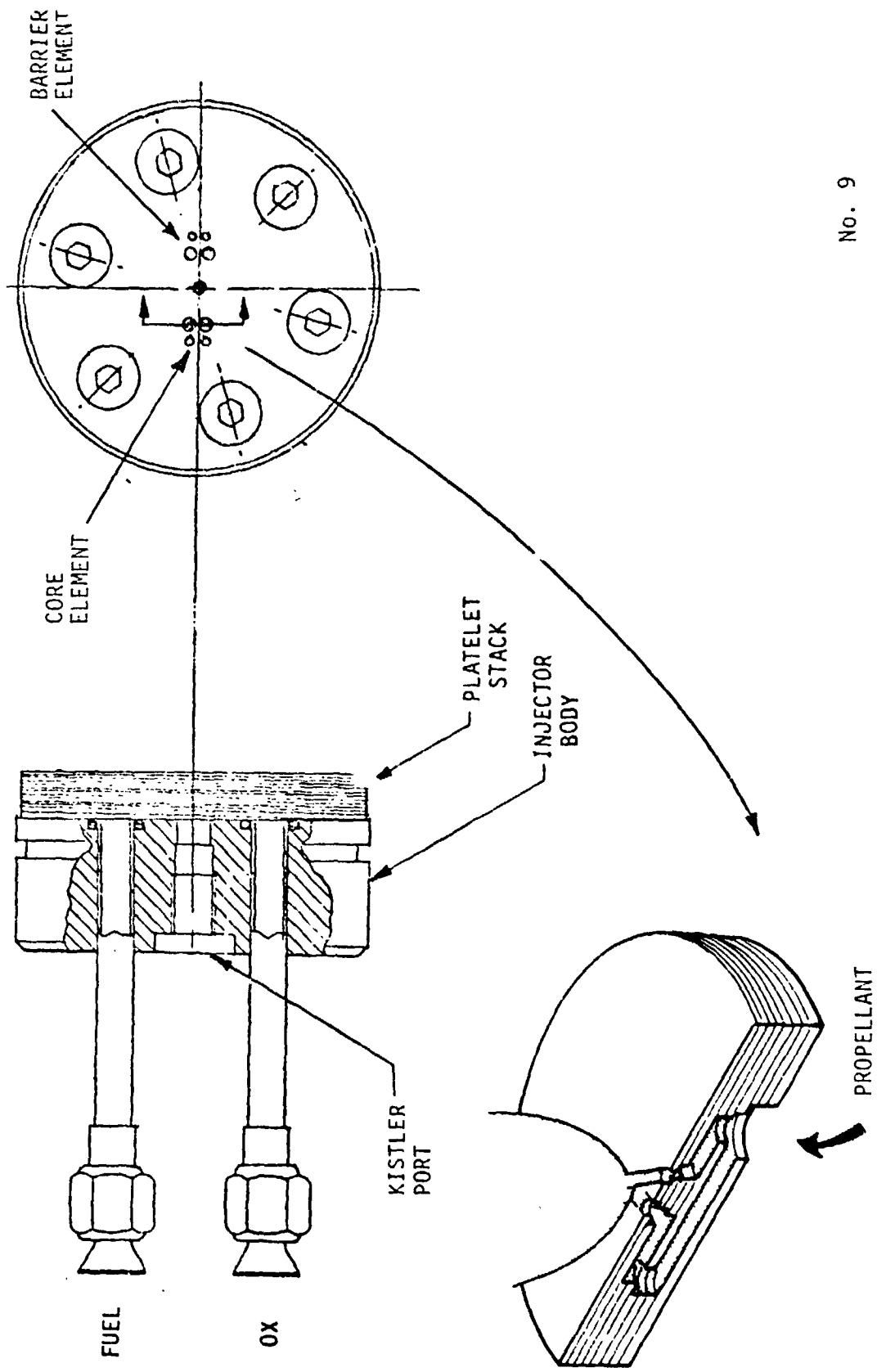
Figure 13. Space Shuttle/OMS TLOL Platelet Injector

BARRIER ELEMENT

CORE ELEMENT

PLATELET STACK

INJECTOR BODY

KISTLER PORT

FUEL

OX

PROPELLANT

No. 9

33

HYCAM HIGH SPEED CAMERA

TEST CHAMBER

1000 WATT QUARTZ/IODINE LAMPS

Figure 14. Hot Fire Test Setup
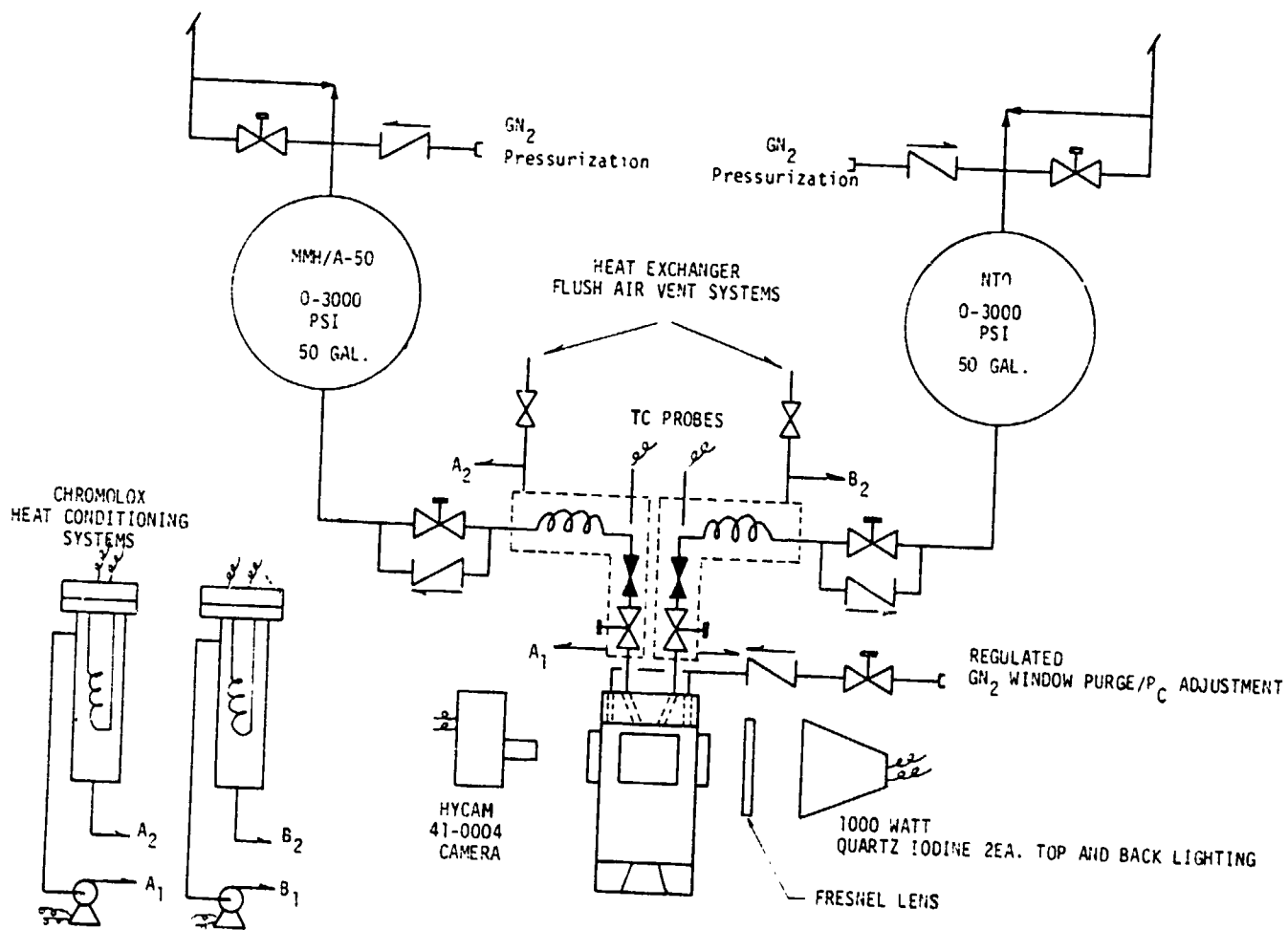
Figure 15. Propellant Flow System Schematic

VI, A, Experimental Hardware and Test Setup (cont.)

systems was used to provide controlled run conditions over a wide range
of injector and chamber pressures.

Propellant conditioning was provided by installing
in-line heat exchangers immediately upstream of the thrust chamber valves.
A hot water circulation type temperature conditioning system was used to
provide independent conditioning of the ox and fuel to temperatures from
ambient to 300°F.

A separately regulated GN_2 supply was used to provide
test chamber back pressure as well as provide window purge for the chamber
viewports during the Task III testing. The window purge was eliminated early
in the Task IV testing to improve photographic quality.

3. Cold Flow Test Setup

The cold flow tests were also conducted in the ALRC
Research Physics Laboratory. Filtered, de-ionized water was used as the
test fluid on most tests. Pressure measurements were made using Heise
pressure gages and flow rate was measured using a time/volume technique,
with run times of from 60 to 200 seconds. Strobe light photographs were
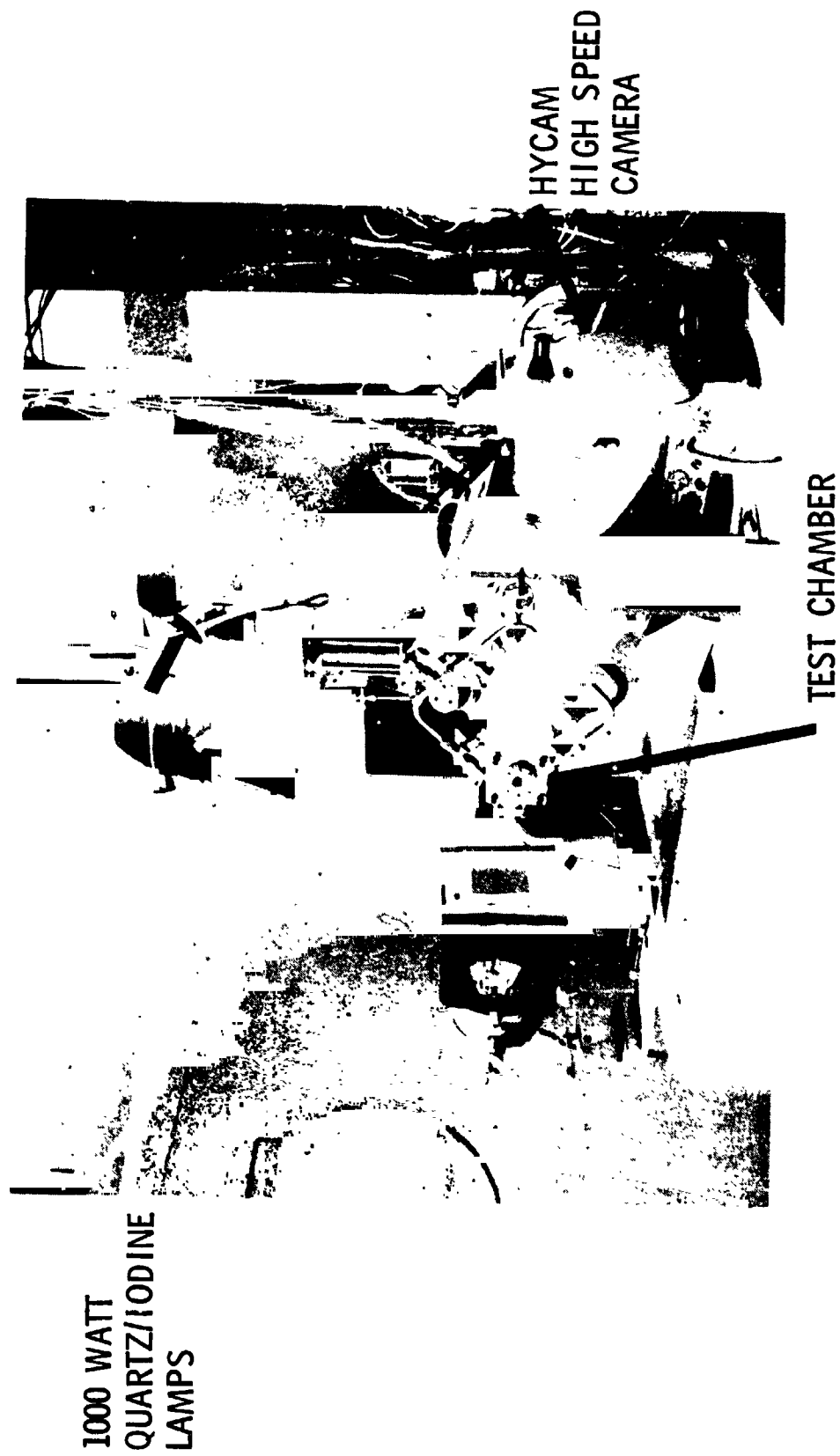taken of some of the injector flow tests to better evaluate propellant
stream properties. Selected tests were also made with dyed water and
freon as the test fluids to evaluate non-reactive stream impingement charac-
teristics.

4. Hot Fire Instrumentation

The high frequency and low frequency instrumentation
listed in Tables II and III were used in the locations shown in the sche-
matic of Figure 16. Low frequency response test parameters were recorded

36

TABLE II

HIGH FREQUENCY RESPONSE INSTRUMENTATION

| Test Parameter | Instrument | | | Range | Accuracy |
	Symbol	Make	Model		
Oxidizer Manifold Pressure	POJHF	Kistler	601	0-3000 psi (P-P)	$\pm$ 0.5%
Fuel Manifold Pressure	PFJHF	Kistler	601	0-3000 psi (P-P)	$\pm$ 0.5%
Chamber Pressure	PCHF	Kislter	601	0-3000 psi (P-P)	$\pm$ 0.5%
Injector Probe Temperature	TP1	C/A		0-1000 °F	$\pm$ 1%

TABLE III

LOW FREQUENCY RESPONSE INSTRUMENTATION

Test Parameter	Symbol	Range	Units	Recorder "O" Graph	Tape	Digital
Oxid. Tank Pressure	POT	0-1500	Psia	X		
Fuel Tank Pressure	PFT	0-1500	Psia	X		
Oxid. Injector Pressure	POJ	0-1500	Psia	X		X
Fuel Injector Pressure	PFJ	0-1500	Psia	X		X
Chamber Pressure	PC	0-1000	Psia	X		X
Window Purge Pressure	PNZ	0-2000	Psia	X		X
Oxid. Flowrate	WO	0-0.1	Lb/sec	X		X
Fuel Flowrate	WF	0-0.1	Lb/sec	X		X
Oxid. Flowmeter Temp.	TOFM	0-500	°F	X		X
Fuel Flowmeter Temp.	TFFM	0-500	°F	X		X
Oxid. Injector Temp.	TOJ	0-500	°F	X		
Fuel Injector Temp.	TFJ	0-500	°F	X		
Oxid. Valve Voltage	VOV			X		
Fuel Valve Voltage	VFW			X		
Wind Purge Valve Voltage	VWPV			X		
Camera Voltage	VCAM			X	X	
Injector Purge Valve Voltage	VIPV			X		
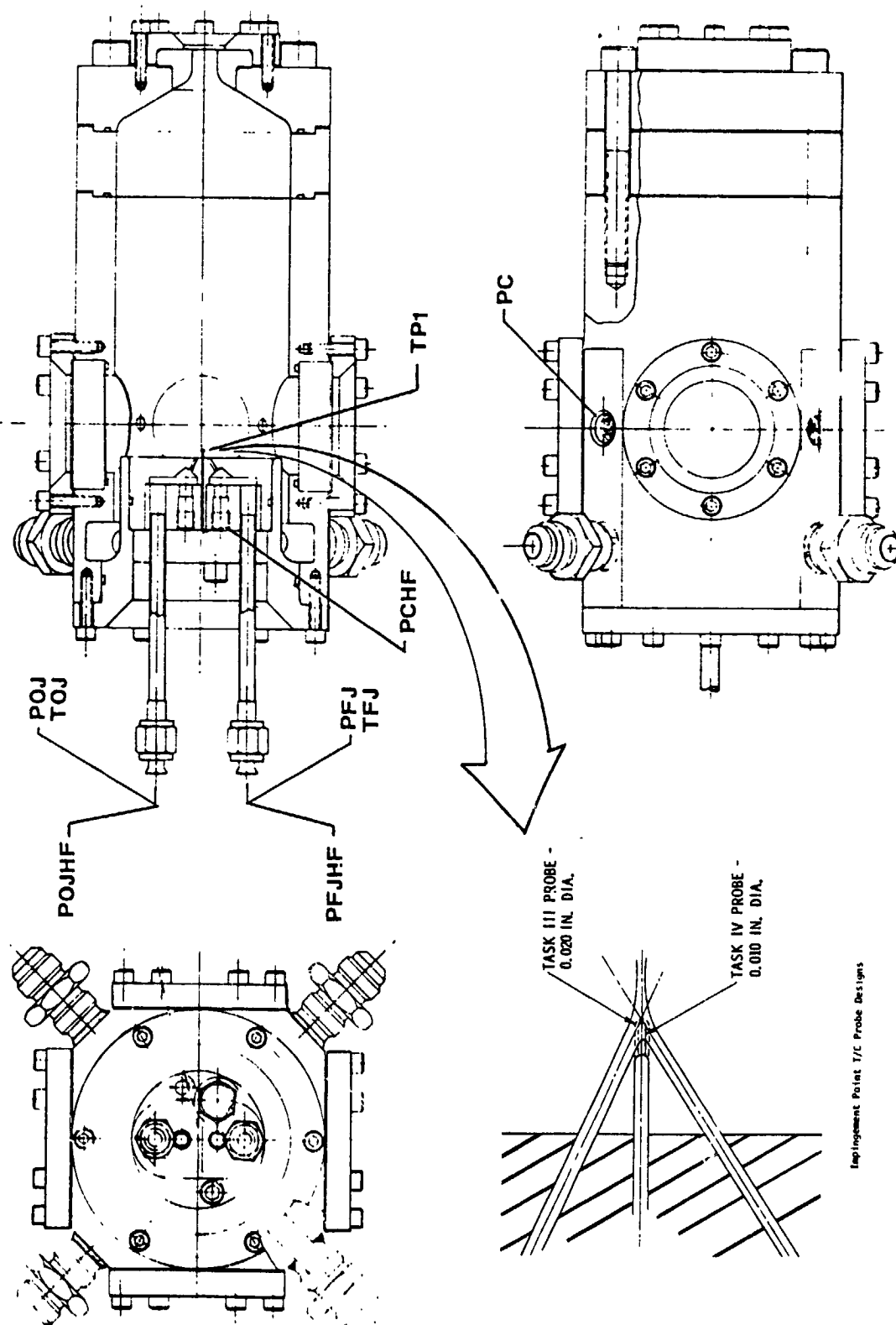
Figure 16. Instrumentation Schematic

TP1

PC

PCHF

POJ
TOJ

PFJ
TFJ

POJHF

PFJHF

TASK III PROBE - 0.020 IN. DIA.

TASK IV PROBE - 0.010 IN. DIA.

Impingement Point T/C Probe Designs

VI, A, Experimental Hardware and Test Setup (cont.)

on a Consolidated Electrodynamic Corporation's direct writing oscillograph.
The high frequency response data were recorded on a Sangamo Model 3564
analog tape recorder.

The propellant flowrates were measured using the injec-
tor cold flow Kw's and the measured injection pressure drops. The pressure
drops were electronically determined from the P_oJ, P_fJ and P_c transducers.
Transducer loss and zero offsets were accounted for by pre-test calibra-
tion. The impingement point temperature was measured during Task III and IV
testing using the probes shown in Figure 16.

The test operating point data were digitized and
stored in an on-line HP 2100 A Computer/Real Time process controller for
"quick look" test review.

B.   PHOTOGRAPHIC EQUIPMENT AND TECHNIQUE

The intent of photographic characterization of injector
element combustion phenomena is to provide an understanding of the physico-
chemical processes that are operative at engine operating conditions. This
necessitates the ability to "look" through the flame to observe the liquid
propellant streams and resultant sprays to determine relative spray mass
and mixture ratio distributions by observing the liquid propellant colors.

It was found that the major problem associated with photo-
graphing combustion flow fields is that the combustion flame light emission
is so intense that it masks the reflected light necessary to see the propel-
lant streams as illustrated in Figure 17. The best technique found for
overcoming the intense combustion light is to reduce the film exposure time
such that the film in effect doesn't "see" the flame light and then to

40

ELECTRIC
HIGH INTENSITY
LAMP

HIGH INTENSITY LAMPS OVERPOWER
FLAME LIGIIT

FLAME LIGHT
EMISSION

REFLECTED LIGHT FROM
EXTERNAL SOURCE MUST
EXCEED FLAME LIGHT
EMISSION INTENSITY
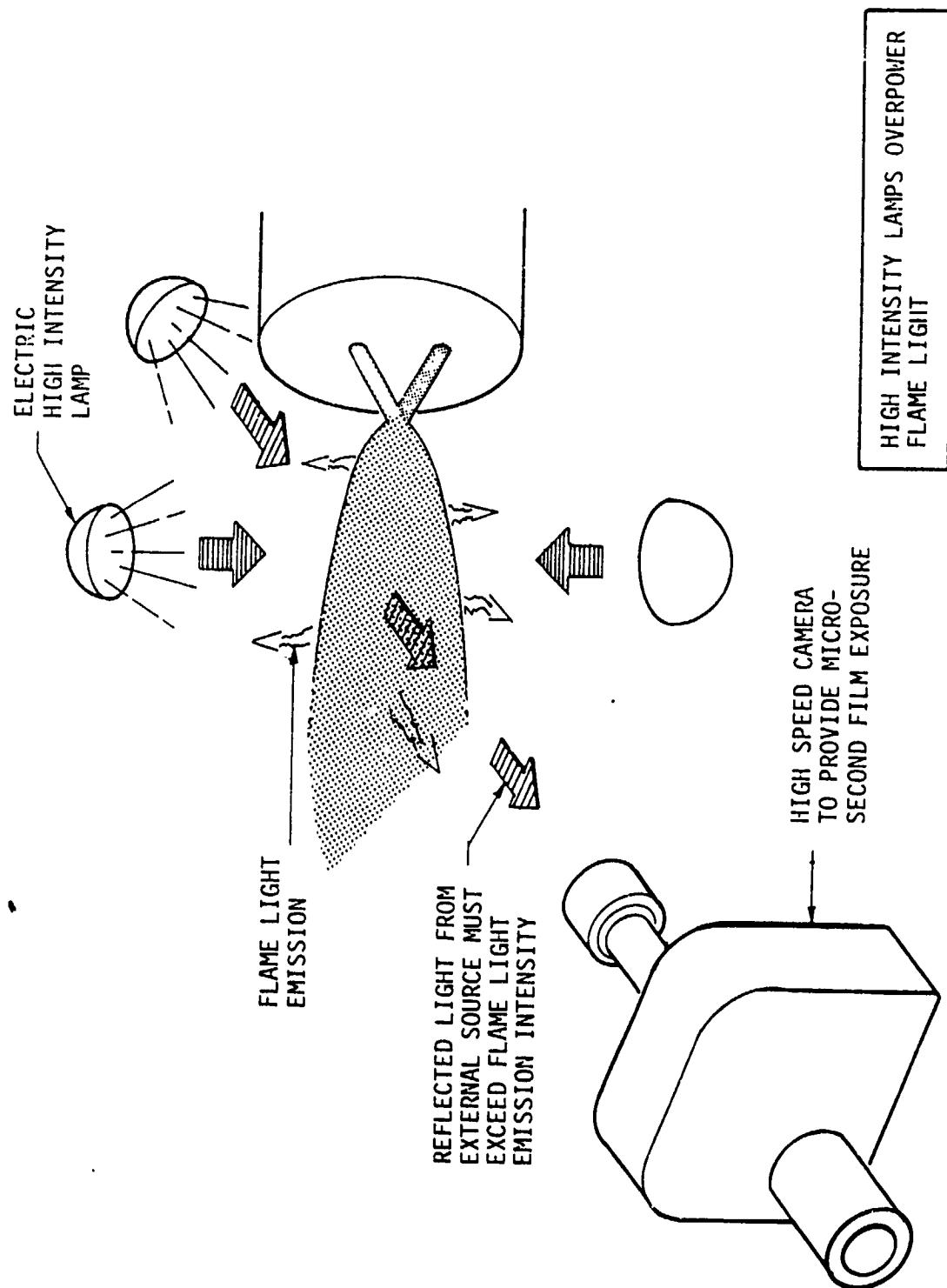
HIGH SPEED CAMERA
TO PROVIDE MICRO-
SECOND FILM EXPOSURE

Figure 17. HighIntensity Lamps Overpower Flame Light Emission

VI, B, Photographic Equipment and Technique (cont.)

provide high intensity external lighting for viewing of the propellant
streams. The external lighting must be provided from the back, top, bottom,
and front to obtain a balance between reflected and absorbed light. It was
found that use of back lighting alone will not provide the lighting balance
required to properly interpret the film.

The photographic combustion characterization was accompl-
ished using the equipment shown in Figure 18. The photographic equipment
is centered around a Hycam model 41-00C4 rotating prism high speed movie
camera. This unique camera has the capability of varying the frame expo-
sure time independent of the film frame rate through a replaceable rotating
shutter. The shutter is mounted to the prism shaft and rotates at the same
speed as the prism. The light exposure at a given frame rate is controlled
by changing the shutter ratio of open time to close time. This is done with
interchangeable shutters. The available shutter ratios are:

1/2.5, 1/10, 1/20, 1/50, and 1/100.

The light exposure time is determined by the product of the shutter ratio
and the reciprocal of the frame rate:

$$\text{Exposure time} = \text{Shutter ratio} \times \frac{1}{\text{P.P.S.}} \text{ (Pictures per sound)}$$

Thus it is possible to obtain exposures of a few microseconds at relatively
low frame rates. For example, most of the photos taken used a 25 usec
exposure and a frame rate of only 800 fps. Some film were taken at frame
rates as low as 400 fps. This capability permits four to five tests to be
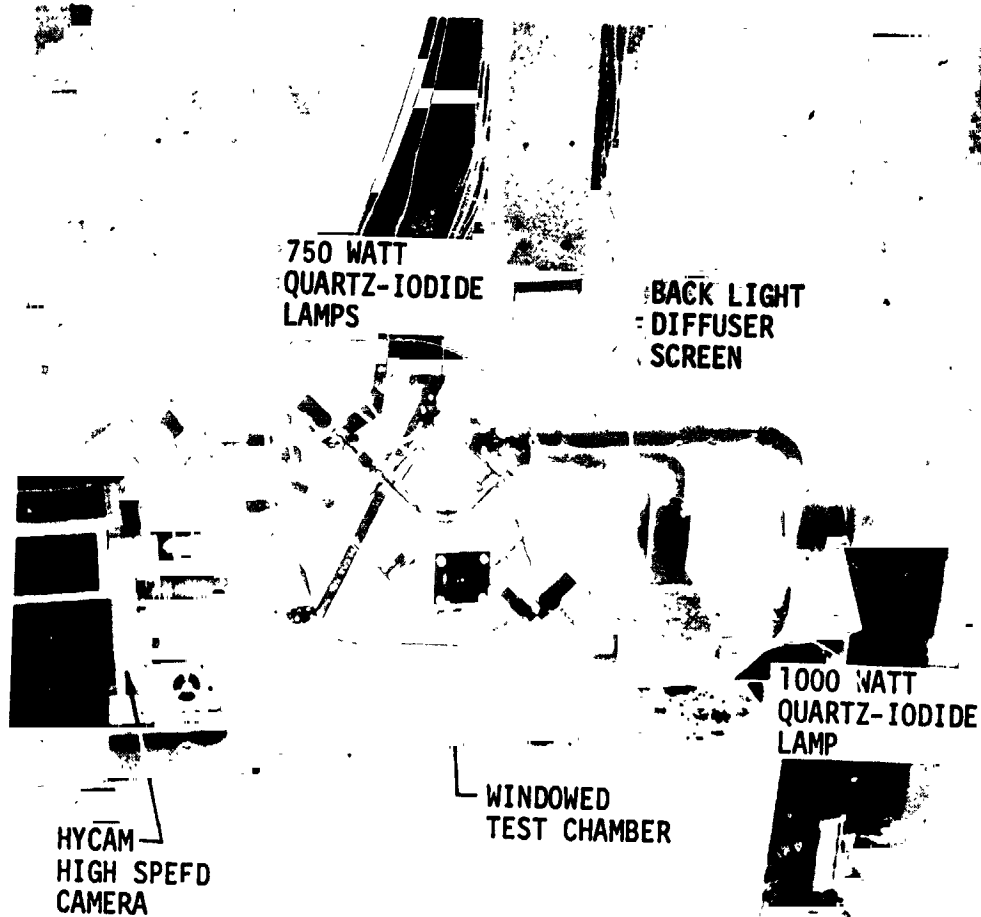filmed on one 400 foot roll of film thus saving film costs.

42

750 WATT
QUARTZ-IODIDE
LAMPS

BACK LIGHT
DIFFUSER
SCREEN

1000 WATT
QUARTZ-IODIDE
LAMP

WINDOWED
TEST CHAMBER

HYCAM
HIGH SPEFD
CAMERA

Figure 18.   Photographic Equipment Setup

VI, B, Photographic Equipment and Technique (cont.)

During Task III pictures were taken over a wide range of frame rates (8000 PPS to 400 PPS) and exposures (1.25 usec to 50 usec) to determine the best operating conditions. It was found that the best pictures were obtained at 400 pictures per second with the 1/100 shutter. A 35mm telephoto lense was used to provide magnification of the spray field. The lense aperature was varied from f/3.3 to f/5.6.

Lighting of the spray field was initially accomplished with the use of three 1000-watt quartz iodine lamps focused with Fresnel lenses as shown in Figure 12. One lamp was used to backlight the spray area with the second and third lamps used as top and front lighting to provide spray detail and definition. The lighting was improved during the Task I' testing by replacing the front and top lights with smaller 750 watt lamps and adding another lamp to light the bottom port as shown in Figure 17. The smaller lamps were placed within one inch of the top and bottom windows to minimize the illumination. The net effect was to improve the balance between the front lighting and the back lighting. Proper balance between the background, side and front lighting is essential to good quality photos.

The frame rate was increased to 800 PPS and the shutter opened to 1/50 during Task IV to further improve the photographic quality. Also during Task IV the GN_2 purge which had been used during the Task III testing was eliminated which provided a significant improvement in film quality. The GN_2 purge creates density gradients within the flow field which show up on the film. The effect is as though the field were being viewed through a film of turbulent water. The photos were acceptable at lower pressures (< 200 psia) where the density gradients were not severe but were unacceptable at higher pressures (> 200 psia). The density gradients were first eliminated by replacing the GN_2 purge with a GH_e purge which had a density close to the combustion gas. However, no purge at all was found to be the best solution since that not only avoids the density gradient problem

VI, B, Photographic Equipment and Technique (cont.)

but also permits the windows to heat up thus eliminating liquid condensation on the window.

Kodak Ecktachrome Type EFB tungsten (3200°K) color film was used. Four hundred foot rolls of the No. 7242 film was selected to provide adequate viewing time. The film has an ASA 125 rating.

C.   TEST RESULTS

A total of 356 hot firings were conducted using the injector elements and fuels listed in Table I. Cold flow tests were also conducted to determine the injector element hydraulic resistances and to characterize non-reactive impingement phenomena.

1.   Cold Flow Test Results

a.   Hydraulic Characteristics

Each of the injectors were cold flow tested to determine their hydraulic resistance and to verify impingement accuracy. The cold flow tests were conducted in the Research Physics Laboratory. Filtered, de-ionized water was used as the test fluid on most tests. Pressure measurements were made using Heiss pressure gages and flow rate was calculated using a time/volume technique, with run times of from 60 to 200 seconds. Strobe light photographs were taken of the elements to evaluate propellant stream properties.

The hydraulic resistances were determined for each of the elements from plots of flowrate versus pressure drop as shown in Figures 19 through 24. The resistance values are summarized in Table IV.

Figure 19.   Pressure Drop Characteristics of the Rounded Inlet
Unlike Doublet Elements

Figure 20. Pressure Drop Characteristics of the Triplet Elements

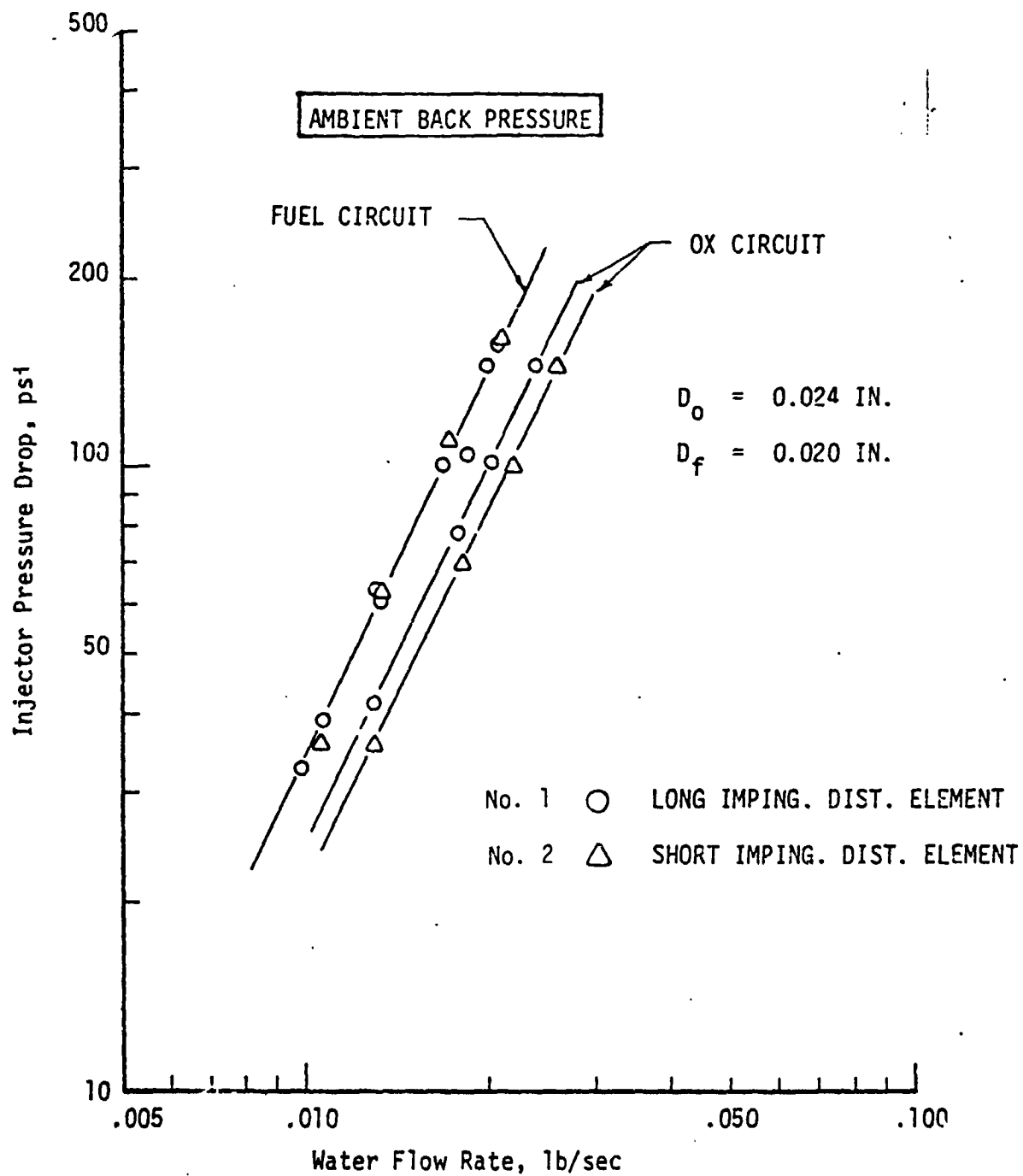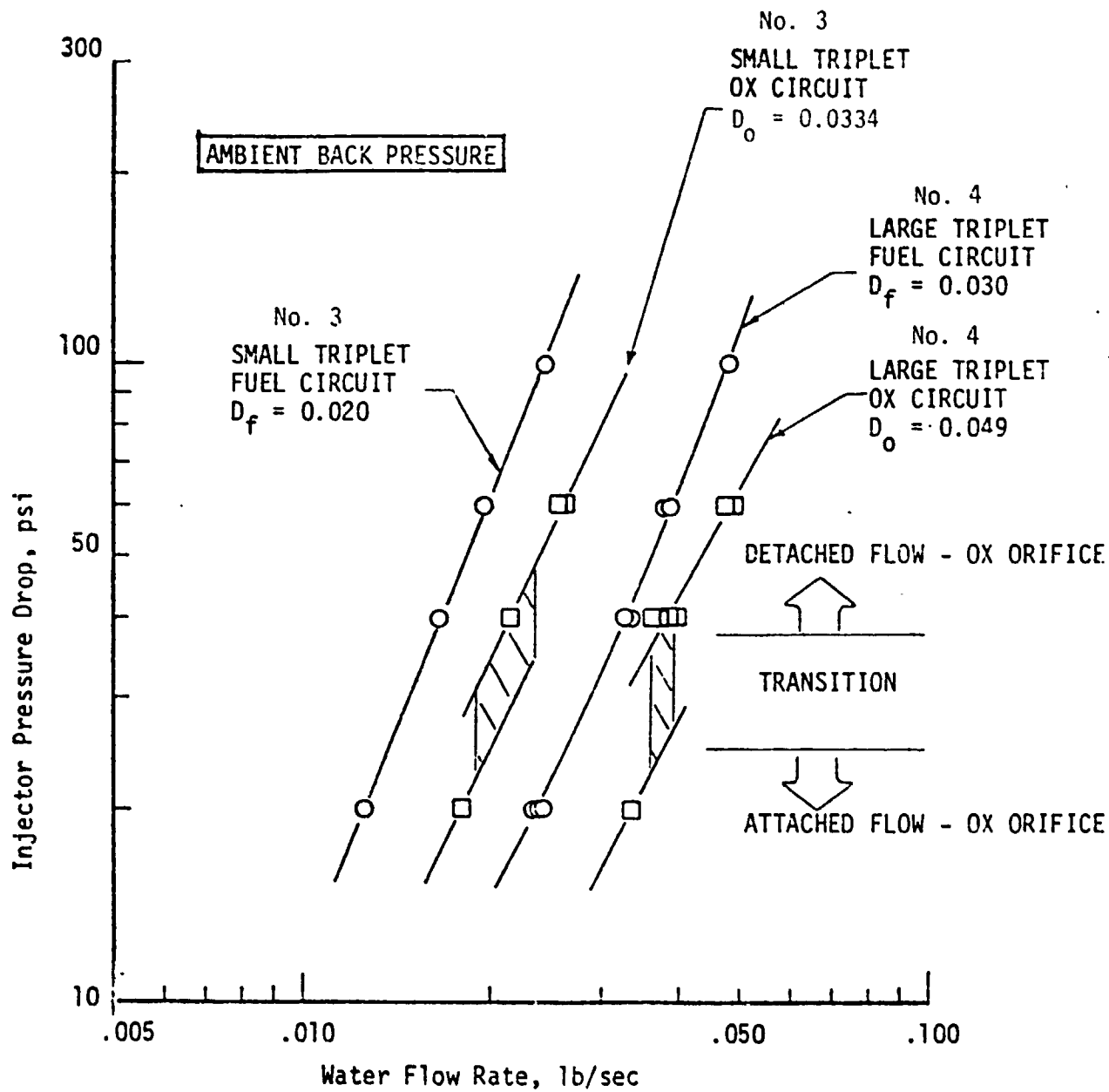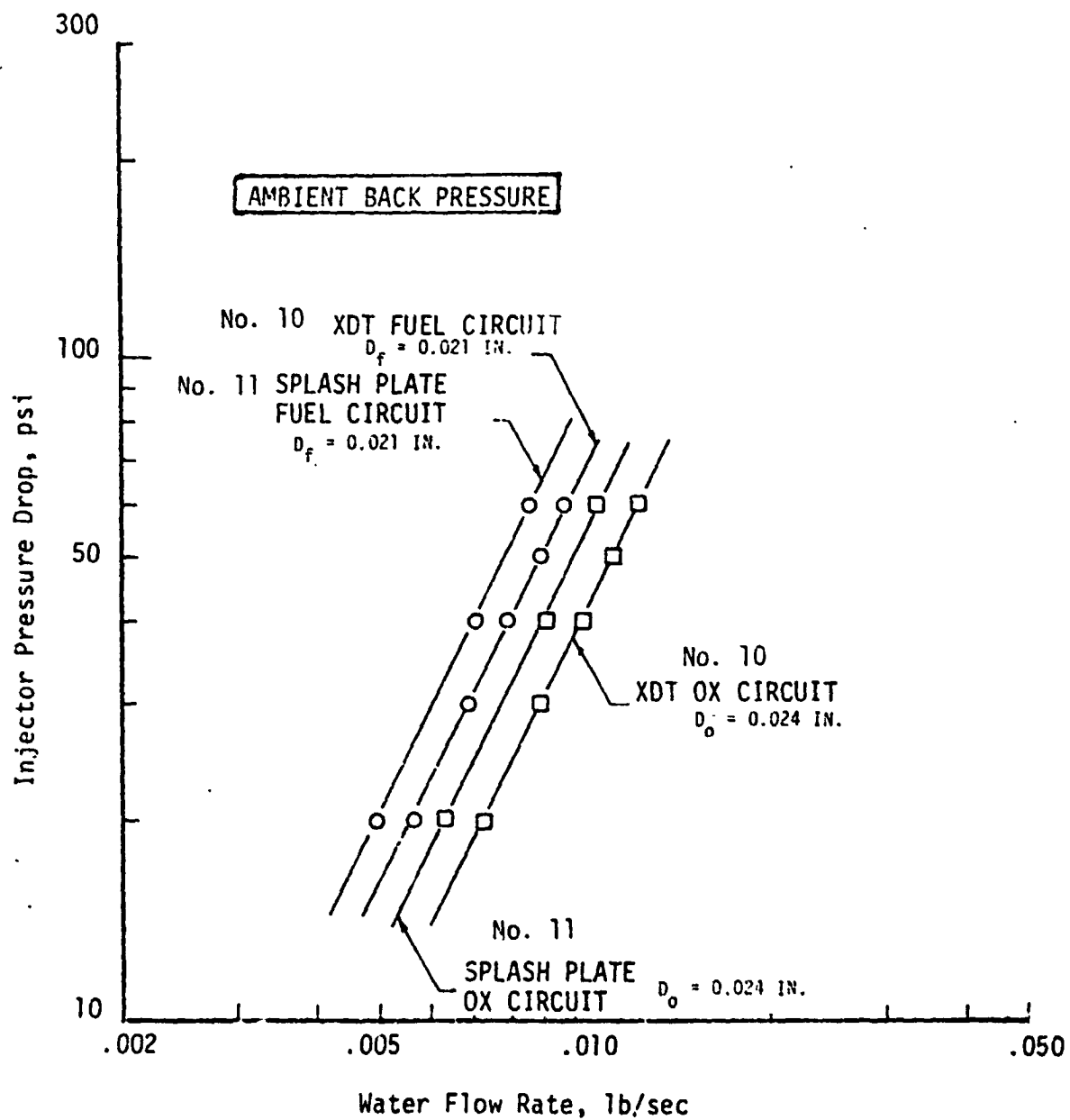Figure 21. Pressure Drop Characteristics of the XDT and Splash Plate Platelet Elements
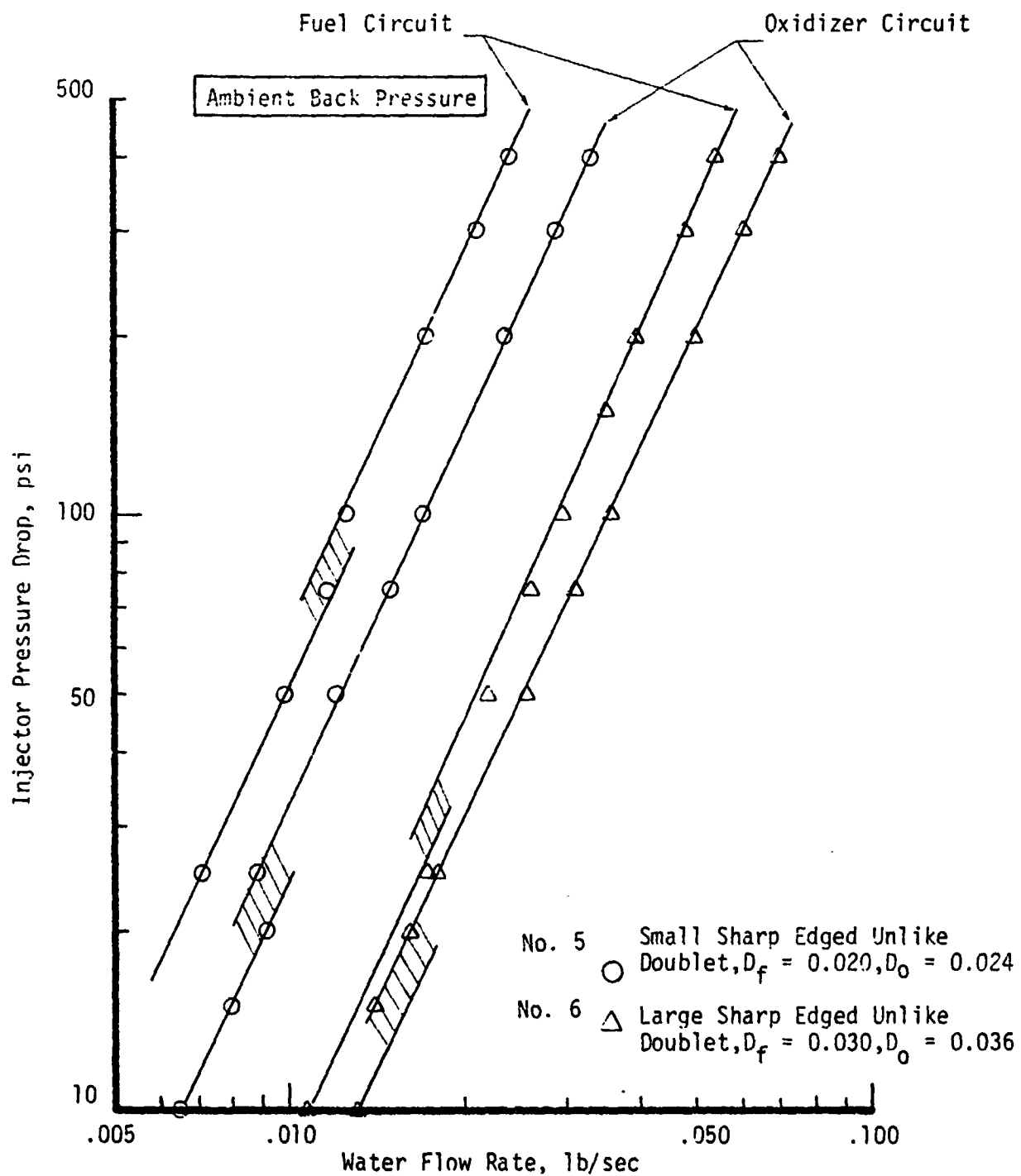
Figure 22.   Pressure Drop Characteristics of the Sharp Edged
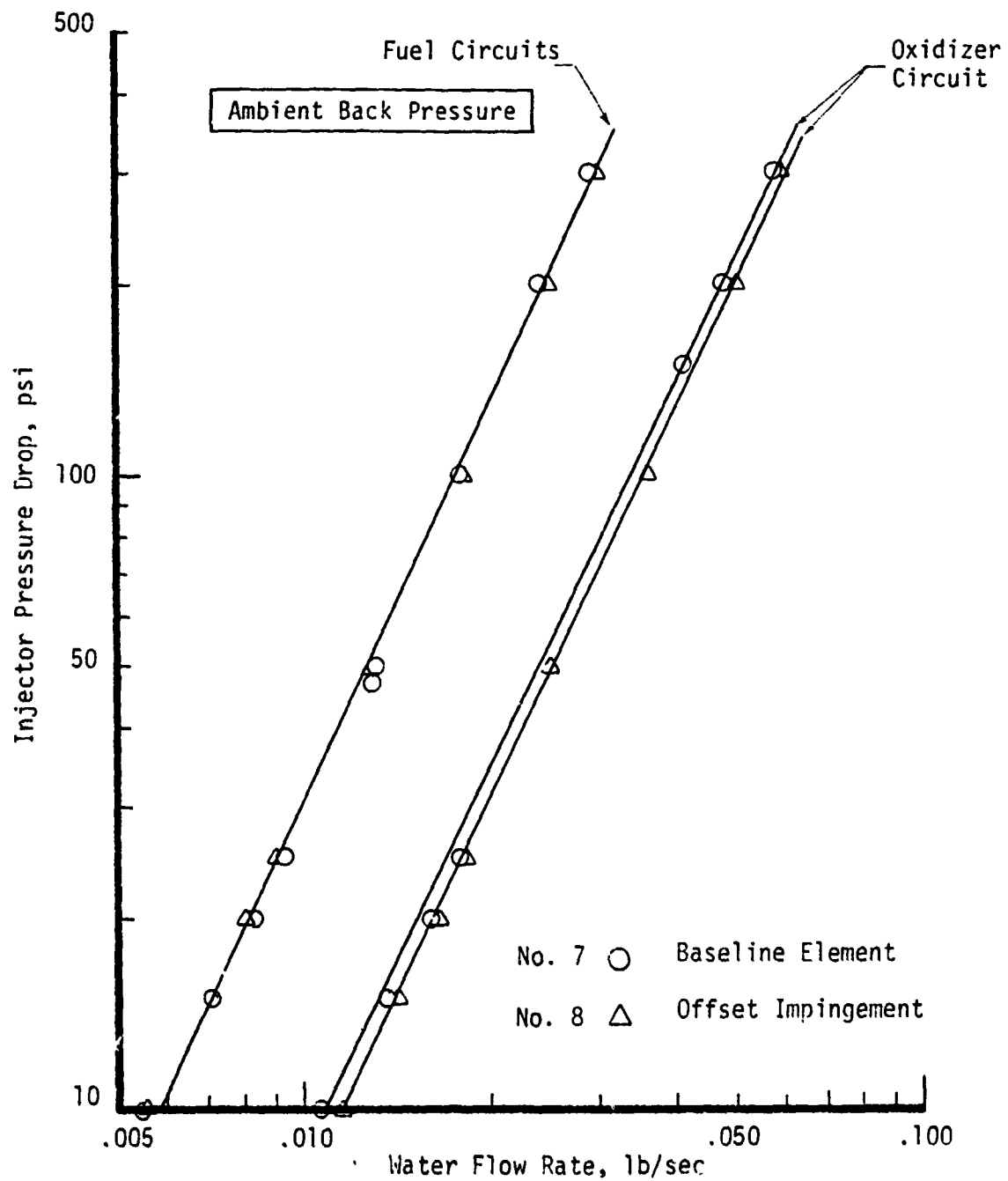Unlike Doublet Elements

49

Figure 23. Pressure Drop Characteristics of the Space Shuttle/RCS Unlike Doublet Elements
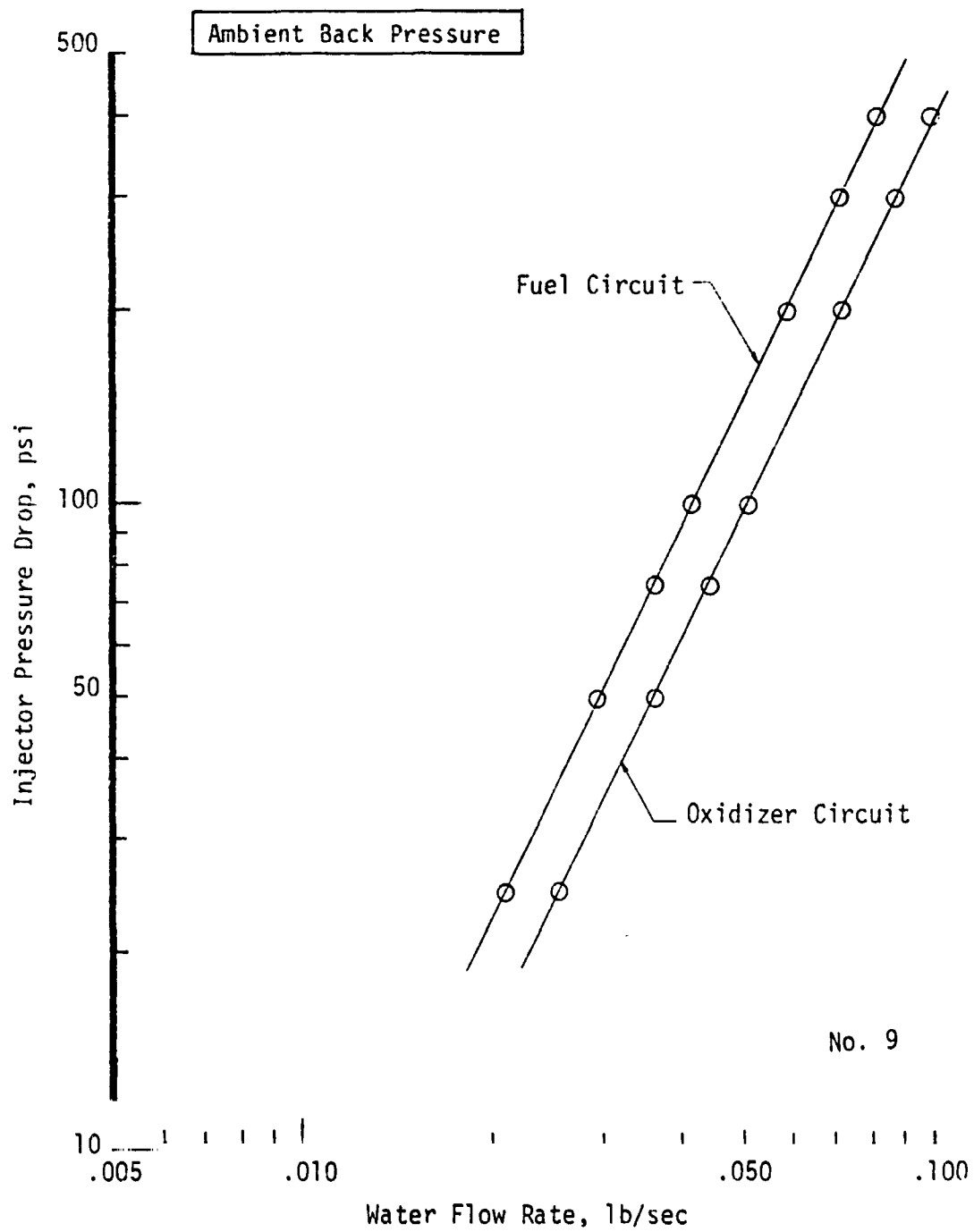
Figure 24.   Pressure Drop Characteristics of the Space Shuttle/OMS
Platelet TLOL Element

TABLE IV

INJECTOR ELEMENT COLD FLOW DATA SUMMARY

Injector	Fuel Orifice		Oxidizer Orifice		
	kW	C_D	kW	C_D	
Rounded Inlet Unlike Doublet, D_f = 0.020 Nos. 1 and 2	0.00169	0.990	0.00215	0.900	
Small F-0-F Triplet D_f = 0.020 No. 3	0.00128	0.772	0.00402	0.838	(Attached)*
			0.00334	0.696	(Detached)
Large F-0-F Triplet D_f = 0.029 No. 4	0.00258	0.715	0.00754	0.751	(Attached)*
			0.00633	0.631	(Detached)
XDT Platelet Element D_f = 0.021 No. 10	0.00125	0.537	0.00162	0.534	(Detached)**
Splashplate Platelet Element D_f = 0.021 No. 11	0.00110	0.602	0.00141	0.591	(Detached)**
Space Shuttle/RCS Unlike Doublet, D_f = 0.023 No. 7	0.00181	0.824	0.00351	0.855	
Space Shuttle/RCS Unlike Doublet, Offset Impingement, D_f = 0.023 No. 8	0.00177	0.808	0.00363	0.883	
Small Sharp Edged Unlike Doublet, D_f = 0.020 No. 5	0.00129	0.780	0.00204	0.856	(Attached)*
			0.00168	0.710	(Detached)
Large Sharp Edged Unlike Doublet, D_f = 0.030 No. 6	0.00326	0.889	0.00418	0.780	(Attached)*
	0.00295	0.790	0.00355	0.660	(Detached)
OMS Engine Platelet TLOL, D_f = 0.028 Core No. 9	0.00409	0.630	0.00502	0.673	(Detached)**

* Injector flowed attached during hot fire tests.
** Injector flowed detached during hot fire tests.

VI, C, Test Results (cont.)

As noted in Table IV some of the orifices were found to flow in a detached mode at ambient back pressures. The platelet elements flow detached by design since their L/D's are less than one. This allows them to flow detached also at hot f. conditions and avoids hydraulic flip.

Some of the triplet and sharp edged unlike doublets flowed detached due to the low ambient backpressure and short orifice L/D (∿4). These orifices were found to flow attached at the hot fire test conditions (i.e., high back pressure). The rounded inlet unlike doublet and the Space Shuttle/RCS element always flowed attached due to the contoured inlets and long L/D's (24/1 and 12/1).

The stream quality of the rounded inlet unlike doublet and the triplet elements are discussed in detail in the interim Report (Ref. 21). The results showed that the rounded inlet unlike doublet flow remains laminar until the Reynolds Number based on the orifice length reaches about 300,000 as predicted by the flow model of Reference 25. The triplet short L/D orifices produce turbulent flow over the whole flow range. It was also found that droplet shedding from the stream surface begins at a Weber Number of 3.0 for the triplet streams as compared to 12.0 for the rounded inlet streams. The more turbulent triplet streams were expected to exhibit RSS more readily than the more coherent rounded inlet unlike doublet streams. However, the final data correlations do not show a significant difference in RSS characteristics between the two injectors.

b.   Non-Reactive Impingement of the Unlike Doublet

The Space Shuttle/RCS unlike doublet injector elements were cold flowed to observe the influence of the intentional 0.003 in. impingement offset. As shown in Figure 25 the 0.003 in offset causes the fan to rotate about 20-30°. The mis-impingement was intended to promote secondary mixing of adjacent propellant spray fans. The mis-impingement appears to promote RSS since the hot firing movies show large amounts of unmixed oxidizer within the chamber. The rotation of the fan caused so much unmixed oxidizer to spray on the viewing window that a clear definition could not be made. It is concluded that misimpingement should be avoided since the resultant spray mixing is impaired.

Spray nonuniformity due to fuel and oxidizer diameter mismatch was another cold flow phenomenon observed with the Space Shuttle/RCS unlike doublet elements. Figure 26 shows stroboscopic still photos of the SS/RCS element cold flow. The large diameter mismatch (D_f = 0.023 and D_0 = 0.0312) produces a "banana" shaped spray distribution which results in two poorly mixed, poorly atomized, oxidizer rich lobes. These oxidizer rich zones are apparent in the hot fire movies.

The effect of off-nominal momentum ratio on the spray distributions is also illustrated in Figure 26. Operation at the fuel rich off-momentum condition is shown in the second photo. The low oxidizer momentum and diameter mismatch cause the oxidizer stream to "umbrella" around the fuel stream resulting in poor mixing. The hot fire results show that these effects coupled with RSS can result in poor performance, stability, and compatibility. The oxidizer rich off-momentum condition produces good mixing due to the splash plate effect of the step in the injector face. The hot fire results confirm the improved mixing at the oxidizer rich condition. It is suspected that if the
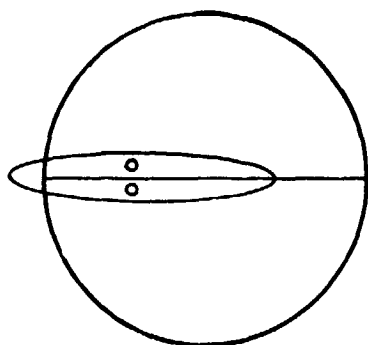
END VIEW

SIDE VIEW

a.   NORMAL IMPINGEMENT

$$\Delta P_{ox} = 21 \text{ PSIG}$$
$$\Delta P_f = 32 \text{ PSIG}$$

$20°-30°$

$0.003"$
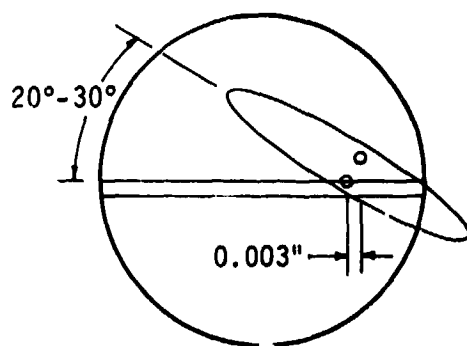
END VIEW

SIDE VIEW

b.   OFFSET IMPINGEMENT

Figure 25.   Impingement Offset Causes Fan Rotation
With the Space Shuttle/RCS Unlike Doublet
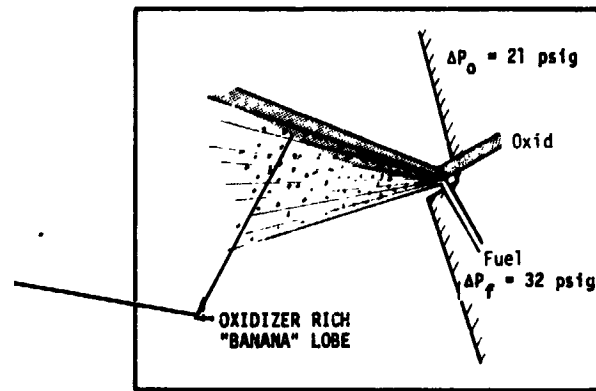
a. Orifice Diameter Mismatch Produces Non-Uniform Spray
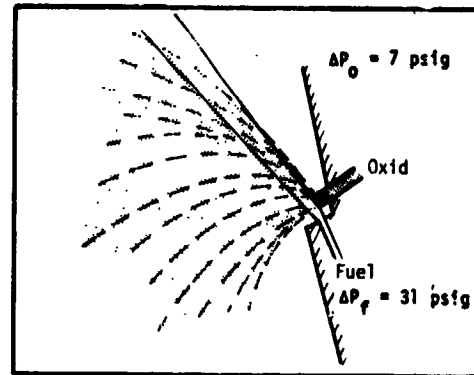
b. Fuel Rich Momentum Condition Causes Oxidizer Stream to "Umbrella" Around Fuel Stream
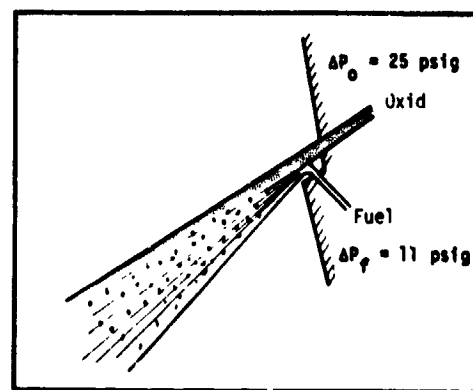
c. Oxidizer Rich Momentum Condition Produces Good Mixing

Figure 26. Space Shuttle/RCS Unlike Doublet Non-Reactive Impingement

56

VI, C, Test Results (cont.)

fuel free stream length were as great as that of the oxidizer stream than
equally poor mixing would occur.

A selected number of cold flow tests were run with
the rounded inlet unlike doublets to film the non-reactive impingement
process to serve as a baseline in interpreting the hot fire movies. The
non-reactive stream impingement is shown in the photograph of Figure 27.
This photograph is an enlargement of a 16mm high speed movie film. The
propellant simulants are dyed water (the blue stream) for fuel and freon
(the clear stream) for oxidizer. The momentum ratio condition is for best
mixing according to the Rupe criteria. (Ref 30). The spray uniformity
attained at the optimum stream momentum ratio condition is clearly evident.
The propellant "shoot-through" (i.e., penetration) phenomena reported by Rupe
is also observed with lower stream momentum as shown in Figure 27. The
"mixing" and "penetration" impingement modes are observed in hot firing and
look a great deal like these cold flow photos, except for the propellant
color differences.

2. Hot Fire Test Results

The hot fire tests were conducted in three separate groups
during Task III, Task IV and Task VII. The test results are included in
Appendix B. Appendix B includes a description of the injector element, the
chamber pressure, the injection velocities and temperatures, the mixture
ratio and the mode of operation. Included are various correlation parameters.
The operation mode is specified as "mix", "separate" (SEP), "mix/separate"
(M/S), "mix/penetrate" (M/P), or "undefined". These modes were identified
from the high speed movies as illustrated in Figure 28 which shows an example
of each of the modes. These photos are blowups of 16 mm movie film.

NOTE
UNIFORM SPRAY

FREON
V = 58 ft/sec
D = 0.026 in.

DYED WATER
V= 79 ft/sec
D = 0.022 IN.

FRAME RATE = 800 fps
EXPOSURE TIME = 25 μs

MIXING UNIFORMITY CRITERIA = 1.0
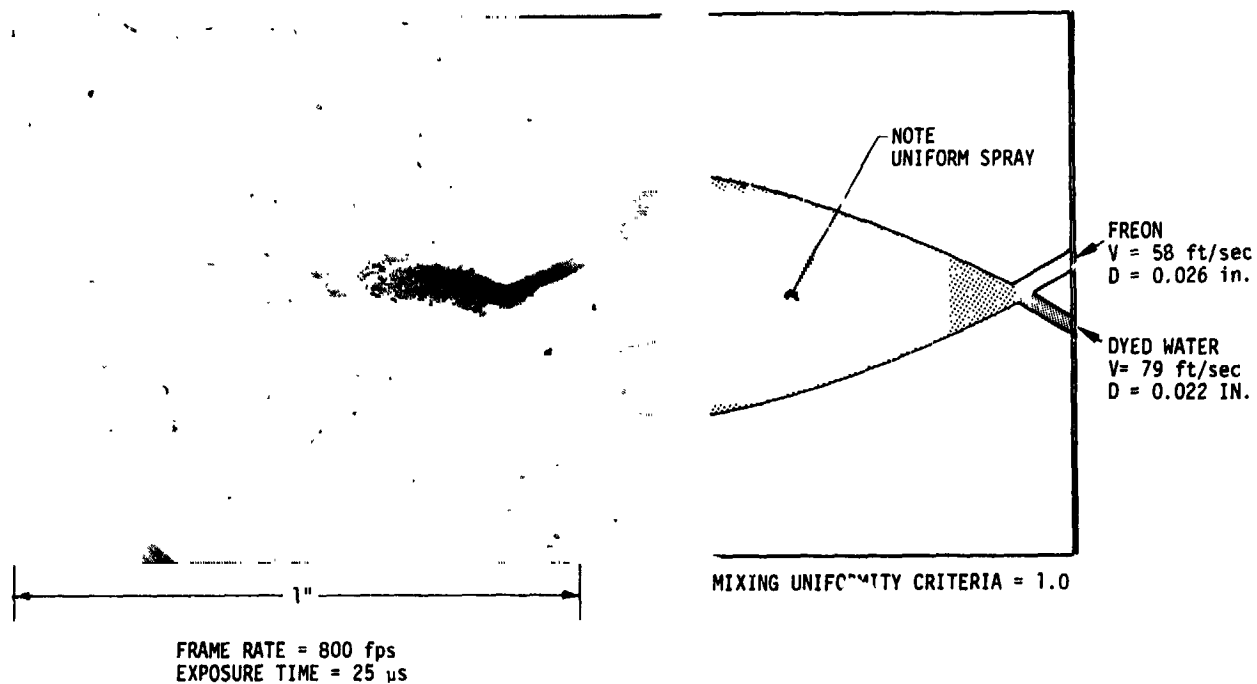
a. Rupe's Mixing Uniformity Criteria Define for Uniform Spary Non-reactive Impingement
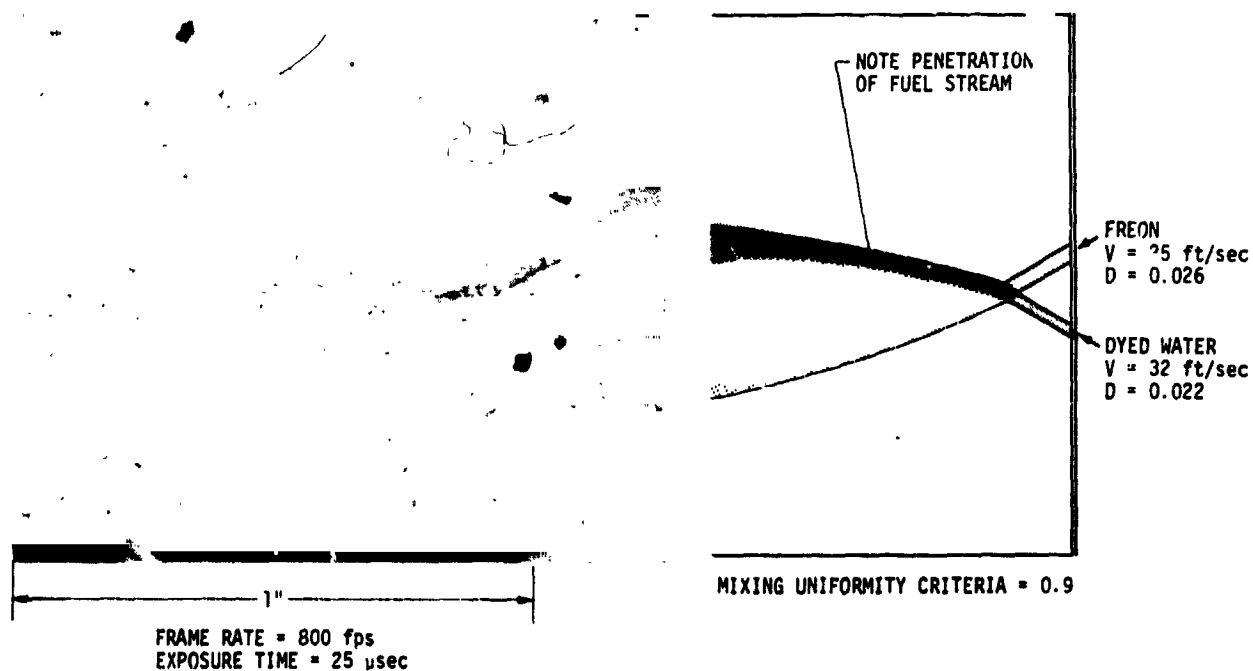
NOTE PENETRATION
OF FUEL STREAM

FREON
V = 25 ft/sec
D = 0.026

DYED WATER
V = 32 ft/sec
D = 0.022

FRAME RATE = 800 fps
EXPOSURE TIME = 25 μsec

MIXING UNIFORMITY CRITERIA = 0.9

b. Low Stream Momentum Produces Penetration Phenomena for Non-reactive Impingement

Figure 27.   Rounded Inlet Unlike Doublet Non-Reactive Impingement

PENETRATE

P_c = 78 psia
V_f = 49 ft/sec
T_f = 75°F
REF = 0.832 x 10^4

N_2O_4

MMH

MIX
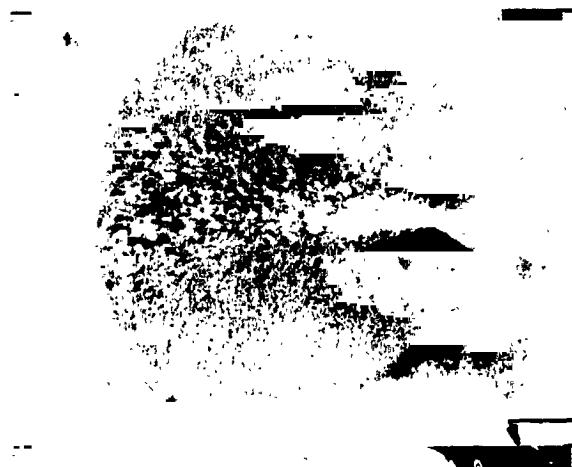
P_c = 124 psia
V_f = 73 ft/sec
T_f = 82°F
REF = 1.32 x 10^4

ROUNDED INLET UNLIKE
DOUBLET D_f = 0.020 in.
D_o = 0.024 in.

MIX/SEPARATE

P_c = 198 psia
V_f = 114 ft/sec
T_f = 76°F
REF = 1.97 x 10^4

SEPARATE

P_c = 144 psia
V_f = 105 ft/sec
T_f = 294°F
REF = 7.72 x 10^4

Figure 28. High Speed Photography Defines Four Modes of
Reactive Stream Impingement

The "Mix/Penetrate" model is characterized by a uni-
form spray field with some propellant penetration as evidenced by an oxidizer
rich zone opposite the oxidizer stream in the downstream spray. "Penetration"
occurs at low injection velocity (less than 50 ft/sec), low fuel temperatures
(below 70°F), and low chamber pressure (less than 100 psia) and is evidenced
by "shoot-through" of the fuel and oxidizer. Penetration has been reported
in earlier cold flow work and was also observed on this program using propel-
lant simulants as well as reactive streams. Penetration is a consequence of
the none-reactive momentum exchange mixing process. "Mixing" is observed
at moderate injection velocities, (50-100 ft/sec) moderate fuel temperatures,
(70-90°F) and moderate chamber pressures (100-200 psia). It is evidenced
by a highly uniform spray field which looks similar to a non-reactive spray
field. "Mix/Separate" occurs at the onset of RSS. It is evidenced by a
slightly non-uniform spray field. "Separation" is observed at higher
injection (greater than 100 ft/sec), higher fuel temperature (greater than
90°F), and higher chamber pressures (greater than 200 psia). It is evidenced
by highly non-uniform spray fields in which distinct regions of unmixed fuel
and oxidizer exist. The "Undefined" designation was assigned to tests where:
(1) movie film were not taken, (2) the injector was improperly rotated in
relation to the camera, (3) or the film could not be interpreted due to poor
visibility. The only film that exhibited poor visibility were those taken
of the SS/RCS unlike doublet with the offset impingement where oxidizer
spray on the window obscured the view. The first few tests within the SS/
RCS injector were run with the injector rotated 90° such that the broad side
of the fan was viewed. Operating modes could not be identified for these
tests.

A total of fifty-one hot fire tests were run during
the Task III testing. The chamber pressure was varied from 80 psia to
1000 psia. The fuel injection velocity was varied from 54 ft/sec to 148
ft/sec. The fuel temperature was run at ambient and 200°F to determine its
effect on RSS. Twelve of the fifty-one tests were run with A-50 to determine
fuel effects on RSS. Temperature probing of the impingement point was done

VI, C, Test Results (cont.)

with a small diameter temperature probe to gain further insight into RSS mechanisms.

The results of the Task III testing showed that RSS depends on the chamber pressure, the fuel temperature, and the injection velocity. Increasing any one of these promotes RSS. Each of these effects were investigated further during the Task IV testing which included testing with the triplet injector and the XDT and splashplate platelet injectors. Additional A-50 testing was also included. One hundred thirty hot fire tests and 10 cold flow tests were run. The results of the cold flow tests are discussed in Section VI.C.1. The results of the Task IV testing confirmed the Task III results.

One hundred sixty four hot fire tests were run during Task VII. The tests included the sharp edged unlike doublet elements, the SS/RCS unlike doublet and the SS/OMS TLOL platelet element. Hydrazine fuel testing was also included with the rounded inlet unlike doublet, the sharp edged unlike doublets, and the SS/OMS TLOL platelet element.

The test results show that: (1) A-50 and N_2H_4 fuel behave like MMH fuel in regards to RSS although combustion of the N_2H_4 fuel is distinctly different as discussed below; (2) increasing the fuel velocity promotes RSS; (3) increasing chamber pressure promotes RSS; (4) increasing fuel tmperature promotes RSS; and (5) self-atomizing/ spray impingement elements promote RSS.

Correlations developed from this data show that RSS is controlled by a vaporization controlled interfacial reaction which is correlated by plotting chamber pressure (Pc) versus fuel orifice Reynolds Number (REF). By plotting the A-50 and N_2H_4 RSS data on these coordinates

it was found that both fuels exhibit the same RSS limit as MMH fuel as shown in Figures 29 and 30.

The combustion of the A-50 fuel is seen to be very similar to that of the MMH fuel by comparing Figure 26 to Figure 27. Whereas, the N_2H_4 combustion is seen to be distinctly different by comparing Figure 30 to Figure 28. The MMH and A-50 combustion are characterized by a zone of yellow combustion at the impingement point followed by droplet vaporization in a blue spray field. The yellow color is due primarily to the NH_2 radical emission caused by decomposition of the fuel. The blue color in the spray field is due to methyl radical emission as a result of bipropellant combustion of the fuel vapors. The N_2H_4 combustion is characterized by both a yellow impingement zone and a yellow spray field. Again the yellow at the impingement zone due to a breaking down of some of the fuel resulting in NH_2 radical emission. The yellow spray field is due to monopropellant combustion of the N_2H_4 droplets which is characteristically yellow due to NH_2 radical emission. The lack of blue emission is due to the absence of methyl radical in the N_2H_4 fuel. Also note the larger quantities of unreacted NO_2 vapors. The N_2H_4 fuel burns primarily in a monopropellant mode leaving only the decomposition products to react with the NO_2 whereas the methylated fuels burn primarily in a bipropellant mode with excess fuel vapor available for combustion with the NO_2.

A significant aspect of the N_2H_4 combustion not visible in the photo of Figure 30 is the observation of the production of solid particles within the impingement zone. The solid particles are evidenced by bright red streaks emanating from the impingement zone. Also visible in some of the film is the production of reaction intermediates on the injector face due to fuel condensation and reaction with the NO_2 vapor. The reaction is characteristic of the surface reactions reported

62

ROUNDED INLET UNLIKE DOUBLET NO. 1

$D_f = 0.020$ in.

$D_o = 0.020$ in.

N_2O_4

T/C PROBE

A-50

MIX

$P_c = 97$ psia

$V_f = 77$ ft/sec

$T_f = 73°F$

REF = 1.13×10^4

1000

SEP

P_c, PSIA   100

N_2O_4/MMH
CORRELATION

MIX

10

10^3 10^4 10^5 10^6

REF

SEPARATE

$P_c = 193$ psia

$V_f = 162$ ft/sec

$T_f = 81°F$

REF = 2.54×10^4
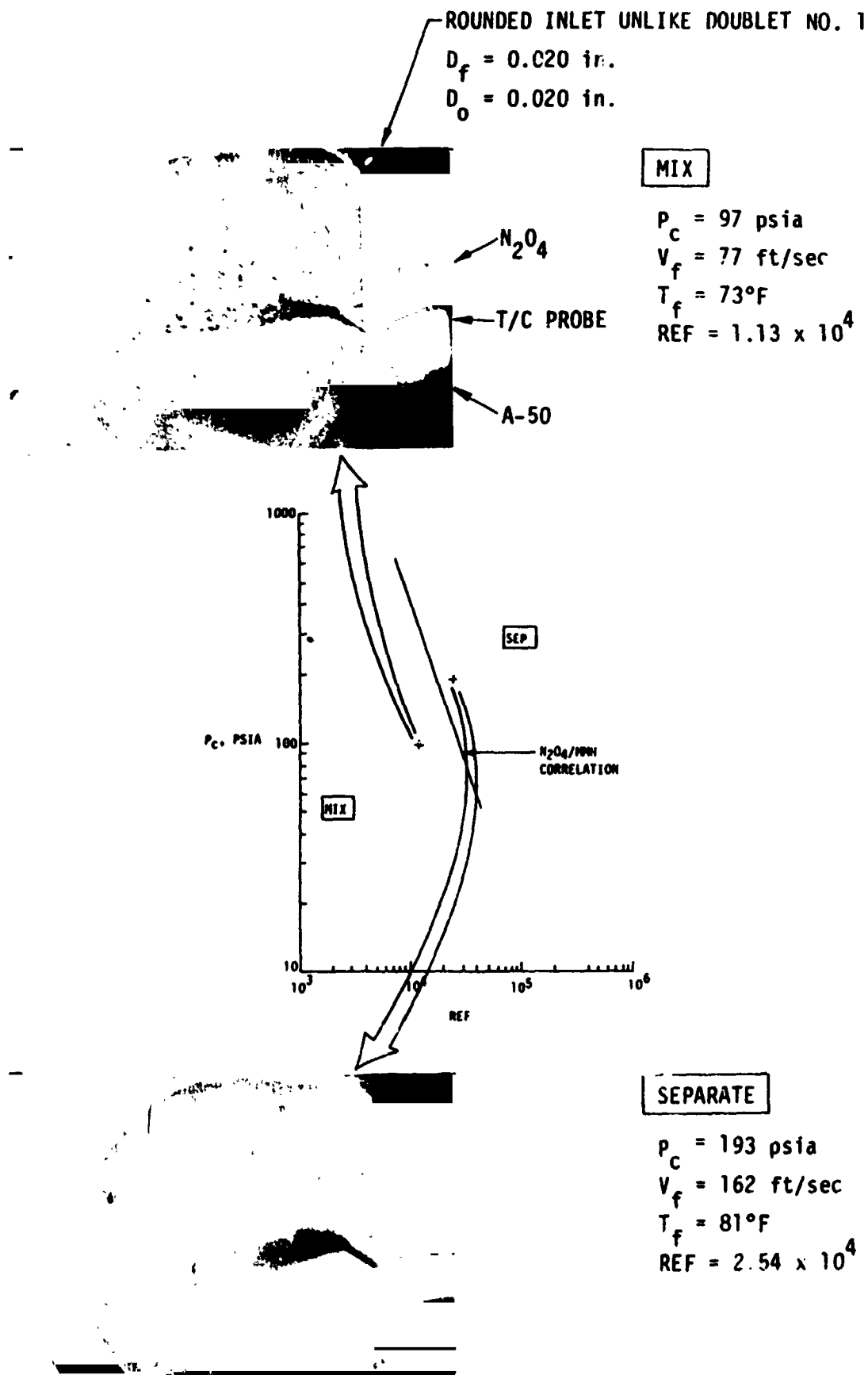
Figure 29. A-50 Fuel Behaves Like MMH Fuel

63

ROUNDED INLET
UNLIKE DOUBLET NO. 1

D_f = 0.020 in.

D_o = 0.024 in.

N_2O_4

N_2H_4

MIX

P_c = 92 psia

V_f = 82 ft/sec

T_f = 68°F

REF = 1.42 x 10^4

SEP

N_2O_4/MMH
CORRELATION

MIX

P_c, PSIA

SEPARATE

P_c = 203 psia

V_f = 98 ft/sec

T_f = 154°F

REF = 3.03 x 10^4
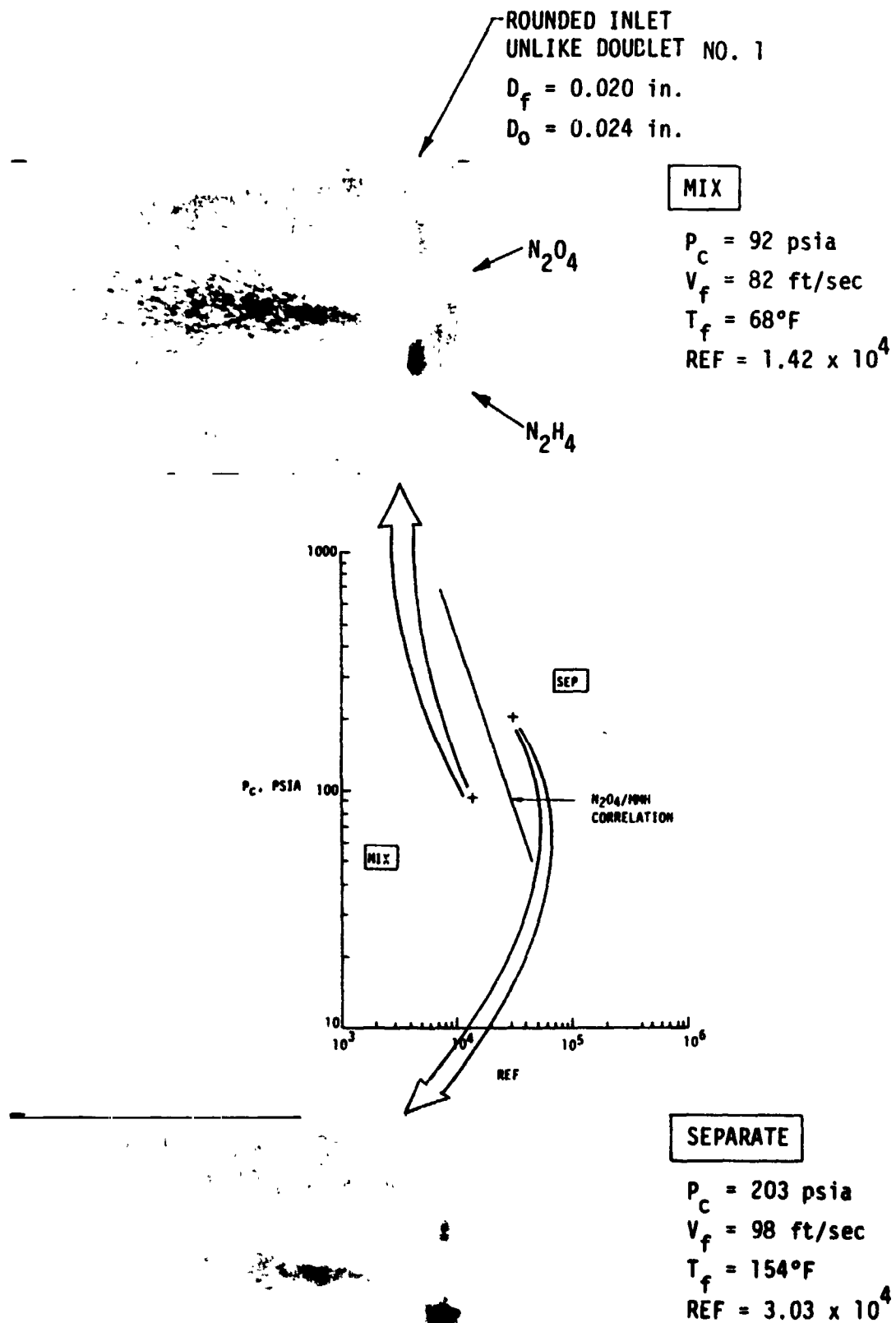
Figure 30. N_2H_4 Fuel Exhibits the Same RSS Limits as MMH Fuel

64

earlier by Zung (Ref. 26) and Lawver (Ref. 27). Observation of the production of reaction intermediates within the impingement zones of the N_2H_4 fuel substantiates the "pop" mechanism proposed during Task I (Ref. 18) and explains the energetic nature of the N_2H_4 fuel as compared to the MMH and A-50 fuels. It is concluded that two separate and distinct mechanisms control RSS and pops. "RSS" is controlled by vaporization limited combustion at the impingement interface whereas "pops" are caused by reaction intermediates formed at the impingement point by surface reactions which subsequently detonate in the spray field. The surface reactions occur with low vapor pressure fuel or under conditions of high heat loss such as with large streams (>0.060 in. dia) and/or cold propellants. Design parameters that affect the reaction rates and resultant intermediate formation, and that would be used to model the "pop" phenomenon include temperature chamber pressure, jet diameter, and injection velocity.

The effect of increasing fuel velocity on RSS is illustrated in the photo of Figure 31. The tests were run at about 200 psia and ambient fuel temperatures using A-50 fuel. The effect of fuel velocity is clearly illustrated by the change in mode from penetration at 50 ft/sec to highly separated at 162 ft/sec. The fuel Reynolds Number increases from 0.707 x 10^4 to 2.54 x 10^4.

Also shown in the photos is a thermocouple probe used to measure the impingement point temperature. The results of the temperature probing showed that the impingement point temperature increases with increasing chamber pressure and injection velocity which is consistent with a vaporization controlled mechanism.

The effect of increasing chamber pressure on RSS is illustrated in Figure 32. The upper photo was taken at a chamber pressure of 97 psia and a fuel velocity of 77 ft/sec with ambient temperature A-50 fuel and is characteristic of the "mix" operating mode. The lower photo was taken at a chamber pressure of 489 psia and a fuel velocity of 104 ft/sec with ambient temperature A-50 fuel. An equivalent test condition with

ROUNDED INLET
UNLIKE DOUBLET
D_f = 0.020 in.
D_o = 0.024 in.

N_2O_4

T/C PROBE

A-50
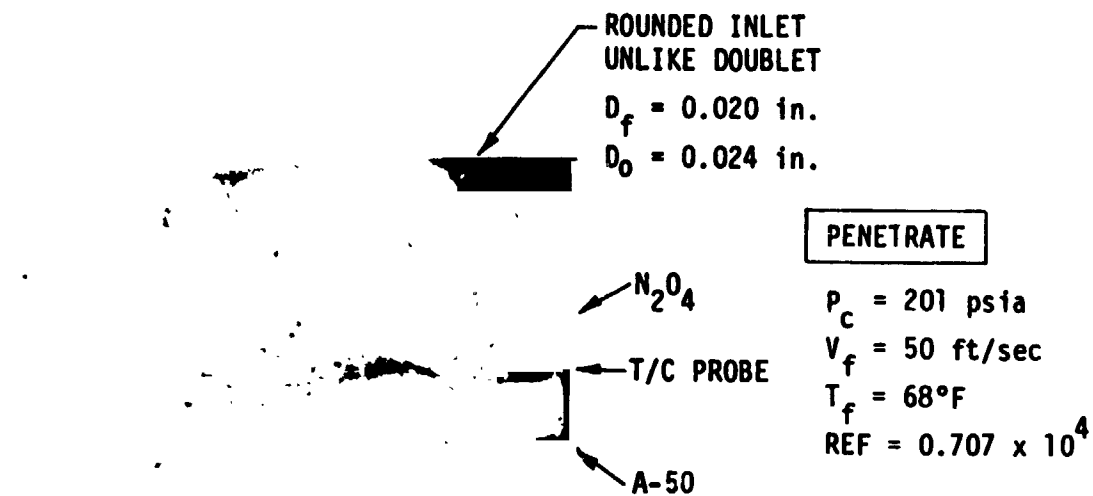
PENETRATE

P_c = 201 psia
V_f = 50 ft/sec
T_f = 68°F
REF = 0.707 x 10^4

MIX

P_c = 199 psia
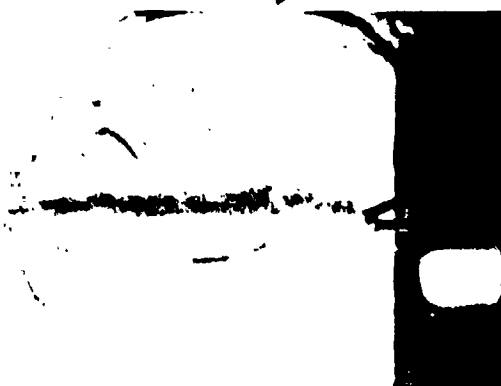V_f = 71 ft/sec
T_f = 69°F
REF = 1.04 x 10^4

SEPARATE

P_c = 193 psia
V_f = 162 ft/sec
T_f = 81°F
REF = 2.54 x 10^4

Figure 31.   Increasing Fuel Velocity Promotes RSS

MIX
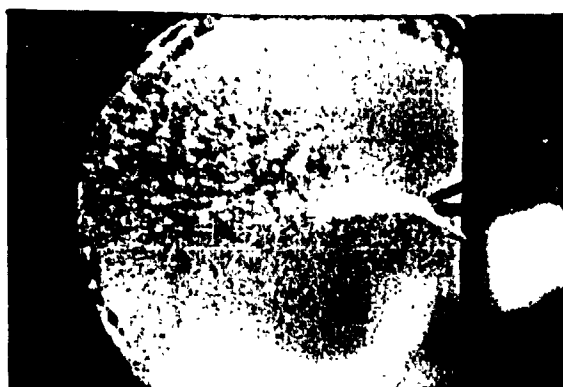
P_c = 97 psia
V_f = 77 ft/sec
T_f = 73°F
REF = 1.13 x 10^4
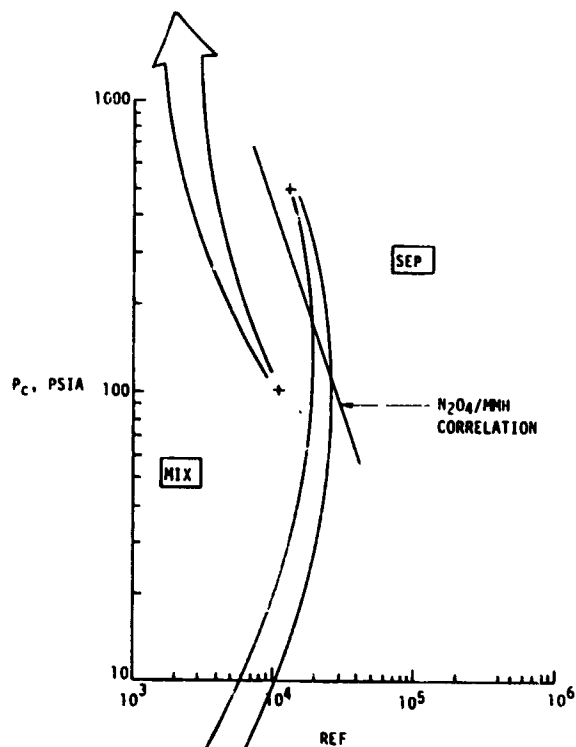
SEPARATE

P_c = 489 psia
V_f = 104 ft/sec
T_f = 70°F
REF = 1.50 x 10^4

Figure 32. Increasing Fuel Temperature Promotes RSS

VI, C, Test Results (cont.)

the same fuel velocity as the lower chamber pressure was not available. However, the difference in REF (1.13×10^4 @ Pc = 97 and 1.50×10^4 @ Pc = 489) between the two tests is not significant since an REF of 1.50 $\times 10^4$ is well within the "mix" regime at 97 psia. Therefore, the primary influence is that of chamber pressure which is seen to cause a high degree of separation at the 489 psia condition.

The effect of fuel temperature on RSS is illustrated in Figure 33 which shows separation induced by high fuel temperatures. The upper photo shows a mixing condition with ambient temperature MMH fuels at a chamber pressure of 147 psia and a velocity of 84 ft/sec. The lower picture shows separation with MMH fuel at a temperature of 294°F and a fuel velocity of 105 ft/sec at Pc = 144 psia. The higher fuel velocity is not enough to induce RSS on its own, therefore the primary influence is due to a fuel temperature increase. As can be seen from Figures 31, 32, and 33, the primary factors controlling RSS are the chamber pressure and the fuel Reynolds Number. Therefore, increasing the fuel velocity, temperature or orifice diameter all tend toward increased RSS.

The RSS characteristics of all of the coherent stream elements (i.e., rounded inlet unlike doublet, triplet, sharp-edged unlike dourblet, and RSS/RCS unlike doublet) were found to be smaller and are correlated with the same correlation equation. The similarity in behavior for the small and large triplets and sharp-edged unlike doublets is shown in Figures 34, 35, 36, and 37. The behavior of the SS/RCS unlike doublet is illustrated in Figure 38 which shows the element behavior over its whole Pc-MR operating range. The impingement mode and operating condition is indicated next to each photo.

The off-mixture ratio momentum effects on spray mixing are seen to be as strong as the RSS effects with the SS/RCS unlike doublet. It is clearly undesirable to operate at extreme off-MR conditions

ROUNDED INLET
UNLIKE DOUBLET

$D_f = 0.030$ in.

$D_o = 0.024$ in.

MIX

$P_C = 147$ psia

$V_f = 84$ ft/sec

$T_f = 75°F$

$REF = 1.44 \times 10^4$

N₂O₄

MMH

1000

SEP

P_c, PSIA   100

N₂O₄/MMH
CORRELATION

MIX

10

10^3 10^4 10^5 10^6

REF

SEPARATE

$P_C = 144$ psia

$V_f = 105$ ft/sec

$T_f = 294°F$

$REF = 7.72 \times 10^4$
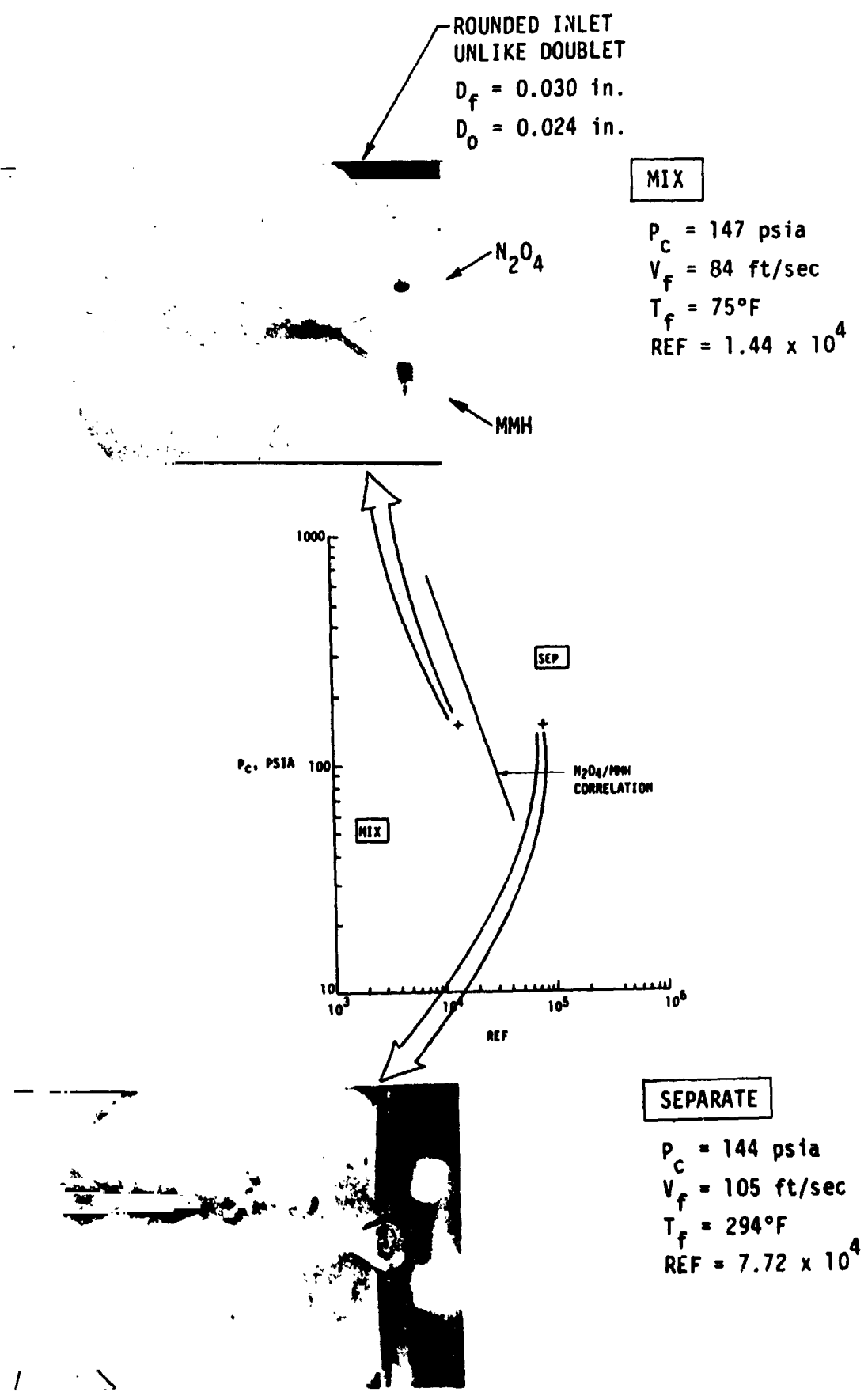
Figure 33.   Increasing Fuel Temperature Promotes RSS

69

SMALL F-0-F TRIPLET NO. 3

D_f = 0.020

D_o = 0.034

MMH

MIX

P_c = 101 psia

V_f = 50 ft/sec

T_f = 80°F

REF = 0.9 x 10^4

N_2O_4

MMH

SEP

P_c, PSIA

N_2O_4/MMH
CORRELATION

MIX

REF

SEPARATE

P_c = 156 psia

V_f = 91 ft/sec

T_f = 296°F

REF = 6.8 x 10^4
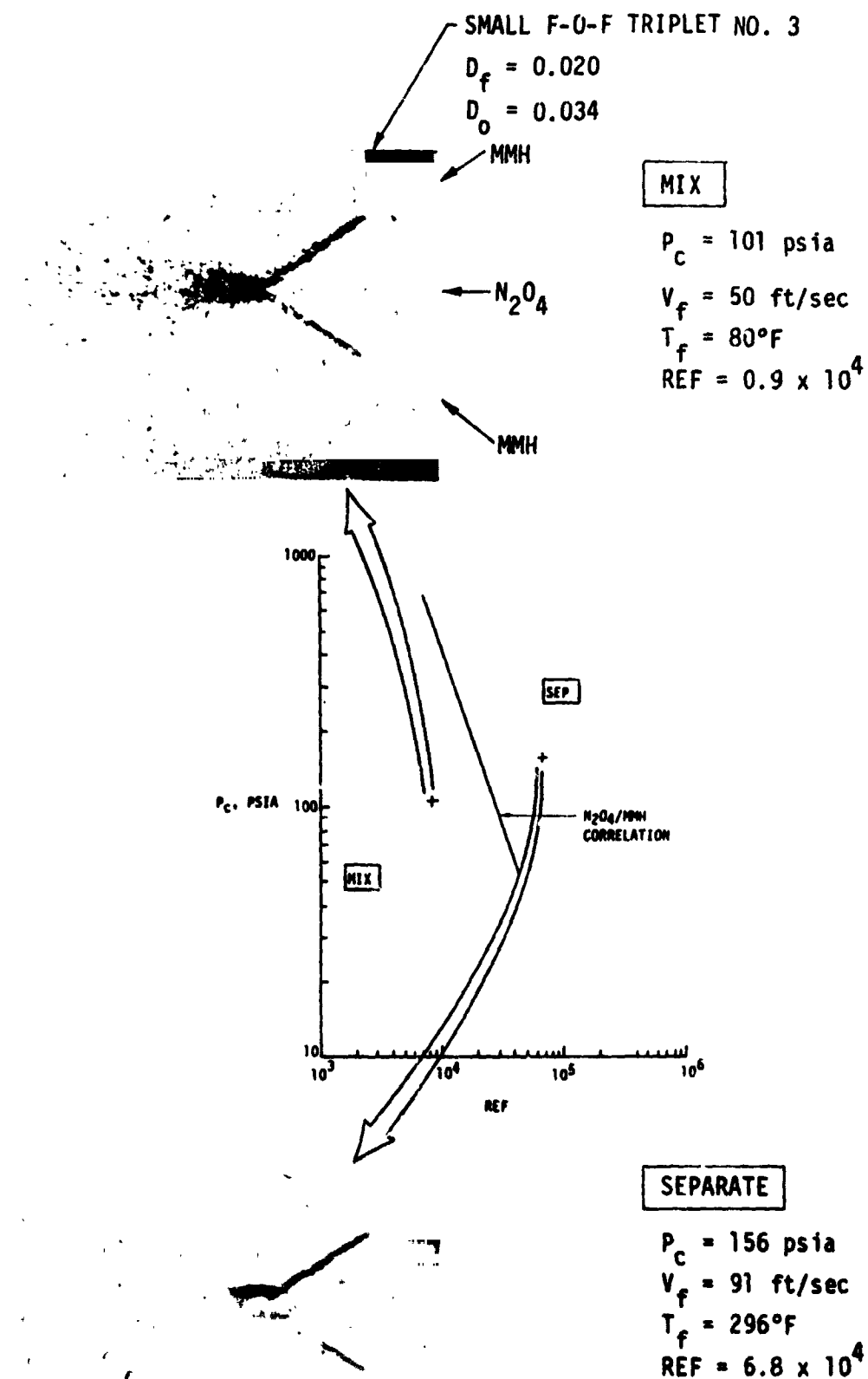
Figure 34.   Reactive Stream Impingement with the Small F-0-F
Triplet Element

70

LARGE F-O-F TRIPLET
D_f = 0.029
D_o = 0.049

MMH

N_2O_4

MMH

MIX

P_c = 129 psia
V_f = 52 ft/sec
T_f = 75°F
REF = 1.3×10^4

1000

SEP

P_c, PSIA   100

N_2O_4/MMH
CORRELATION

MIX

10
10^3 10^4 10^5 10^6
REF

SEPARATE

P_c = 194 psia
V_f = 78 ft/sec
T_f = 69°F
REF = 1.86×10^4
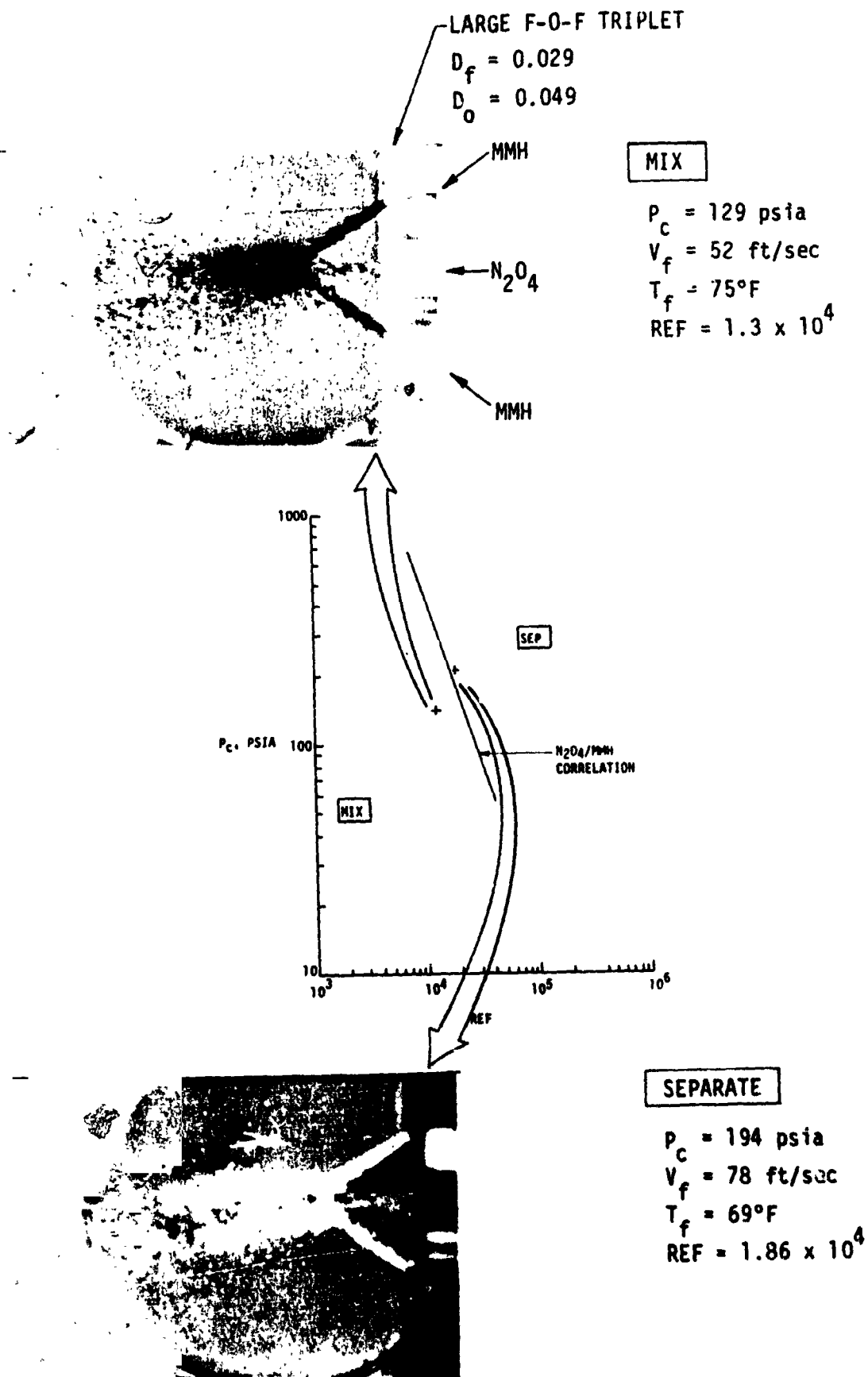
Figure 35.   Reactive Stream Impingement with the Large F-O-F
             Triplet Element

SMALL SHARP EDGED UNLIKE DOUBLET NO. 5

D_f = 0.020 in.

D_o = 0.024 in.

MIX

P_c = 103 psia

V_f = 119 ft/sec

T_f = 70°F

REF = 1.95 x 10^4

SEPARATE

P_c = 191 psia

V_f = 117 ft/sec

T_f = 73°F

REF = 1.97 x 10^4
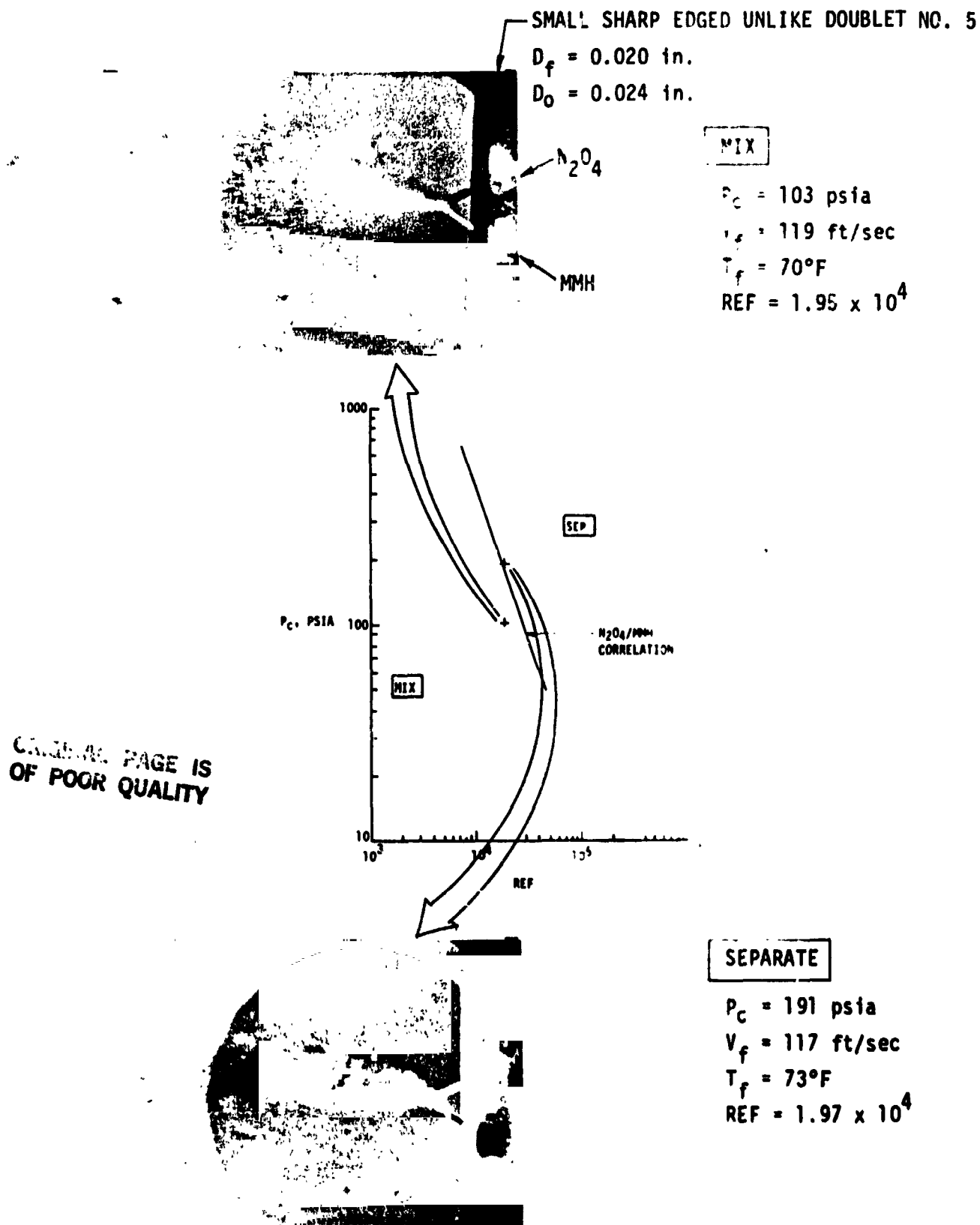
Figure 36.   Reactive Stream Impingement with the Small Sharp
Edged Unlike Doublet

LARGE SHARP EDGED UNLIKE DOUBLET
D_f = 0.030 in.
D_o = 0.036 in.

N_2O_4

MMH
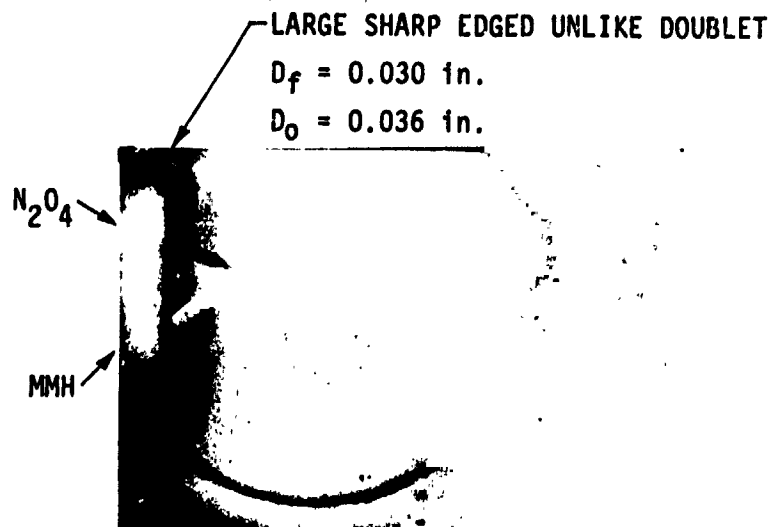
MIX

P_c = 299 psia
V_f = 38 ft/sec
T_f = 69°F
REF = 0.92 x 10^4

P_c, PSIA

SEP

N_2O_4/MMH
CORRELATION
$P_c = 4.4 \times 10^8 (REF)^{-1.5}$

MIX

REF
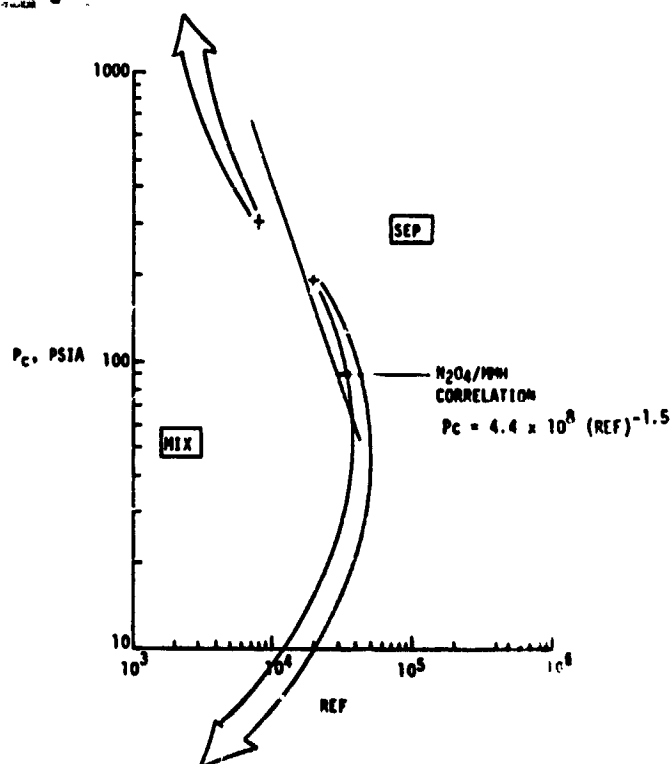
SEPARATE

P_c = 195 psia
V_f = 76 ft/sec
T_f = 77°F
REF = 1.99 x 10^4

Figure 37. Reactive Stream Impingement with the Large Sharp
            Edged Unlike Doublet

73
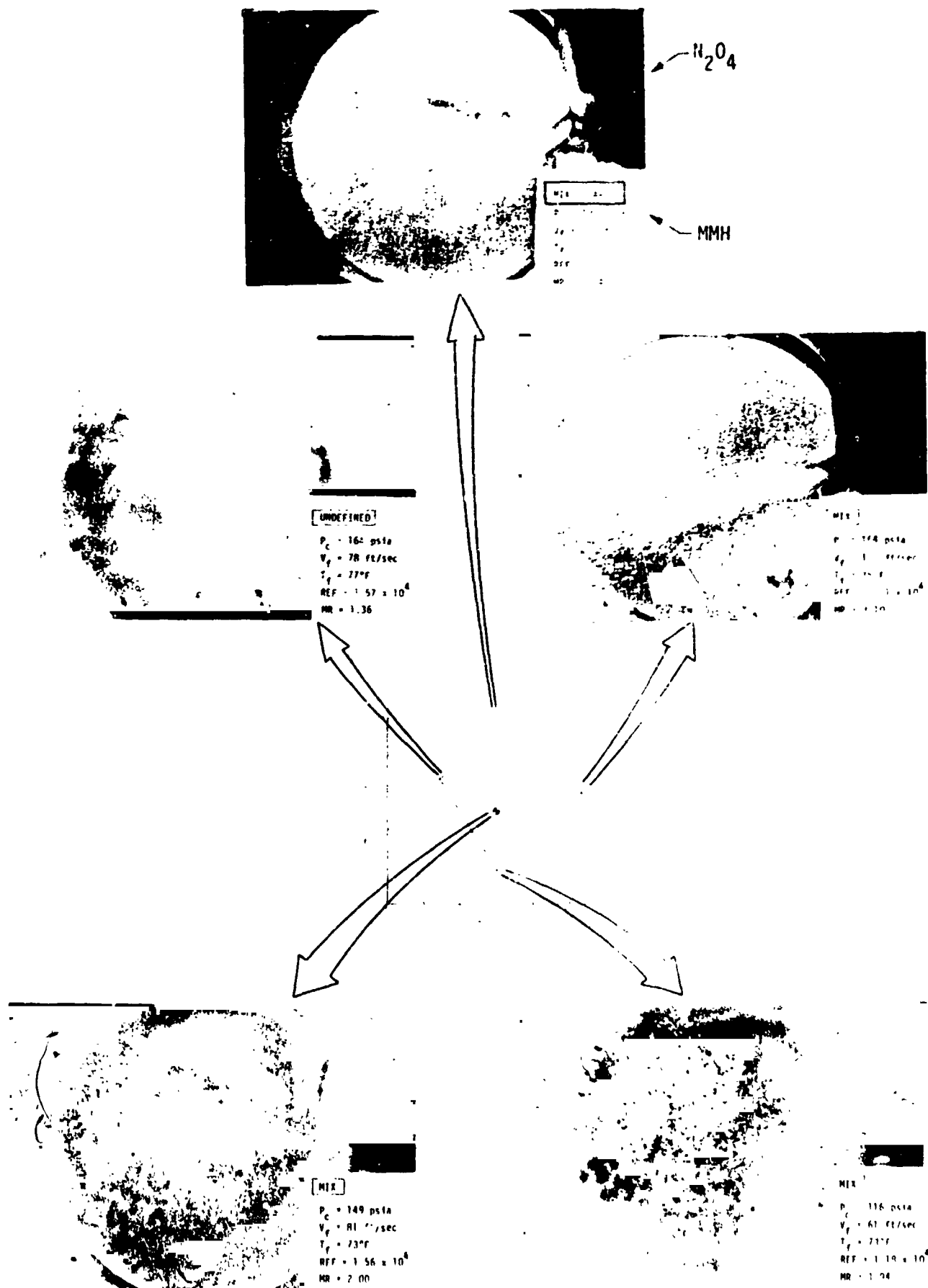
Figure 38.   Reactive Stream Impingement with the Space Shuttle/
OMS Unlike Doublet No. 7

with unlike doublet elements due to the strong effect on spray distributions. The triplet or pentad coherent elements or self-atomizing elements which are less sensitive to RSS and momentum effects would be better choices for injectors that must cover wide mixture ratio ranges.

The RSS Characteristics of the XDT, the splashplate and the SS/OMS TLOL self-atomizing elements were found to differ from the coherent stream elements in that RSS occurs at lower chamber pressures than for the coherent stream elements. The RSS characteristics of the XDT and the splashplate elements are illustrated in Figures 39 and 40. Increasing chamber pressure and fuel Reynolds Number (REF) promotes RSS. The chamber pressure is a much stronger effect than the fuel velocity (REF) as evidenced by the small slope of the correlation line. RSS sets in at such low chamber pressure levels (~100 psia) that these elements generally always operate in the separated mode.

The SS/OMS TLOL platelet element is an example of an element that operates in a separated mode over its entire operating range as illustrated in Figure 41. The operating conditions are indicated next to each photo. It is evident that this element is insensitive to engine operating mode. Although, it is always separated, the desired engine performance is attained by providing element overlap to take advantage of inter-element mixing. Excellent performance, compatibility and storability are provided by this element since the injector spray mass and mixture ratio distribution remain nearly constant over its whole operating range.

The SS/OMS TLOL element was found to operate much the same with N_2H_4 fuel substituted for the MMH fuel as illustrated in Figure 42. The spray distributions are nearly identical over a wide chamber pressure range.

MIX

P_c = 98 psia
V_f = 53 ft/sec
T_f = 71°F
REF = 0.913 x 10^4

SEP

SELF ATOMIZING
ELEMENT
CORRELATION
$Pc \cdot 1279 (REF)^{-0.24}$

MIX

P_c, PSIA

SEPARATE

P_c = 194 psia
V_f = 100 ft/sec
T_f = 97°F
REF = 2.18 x 10^4
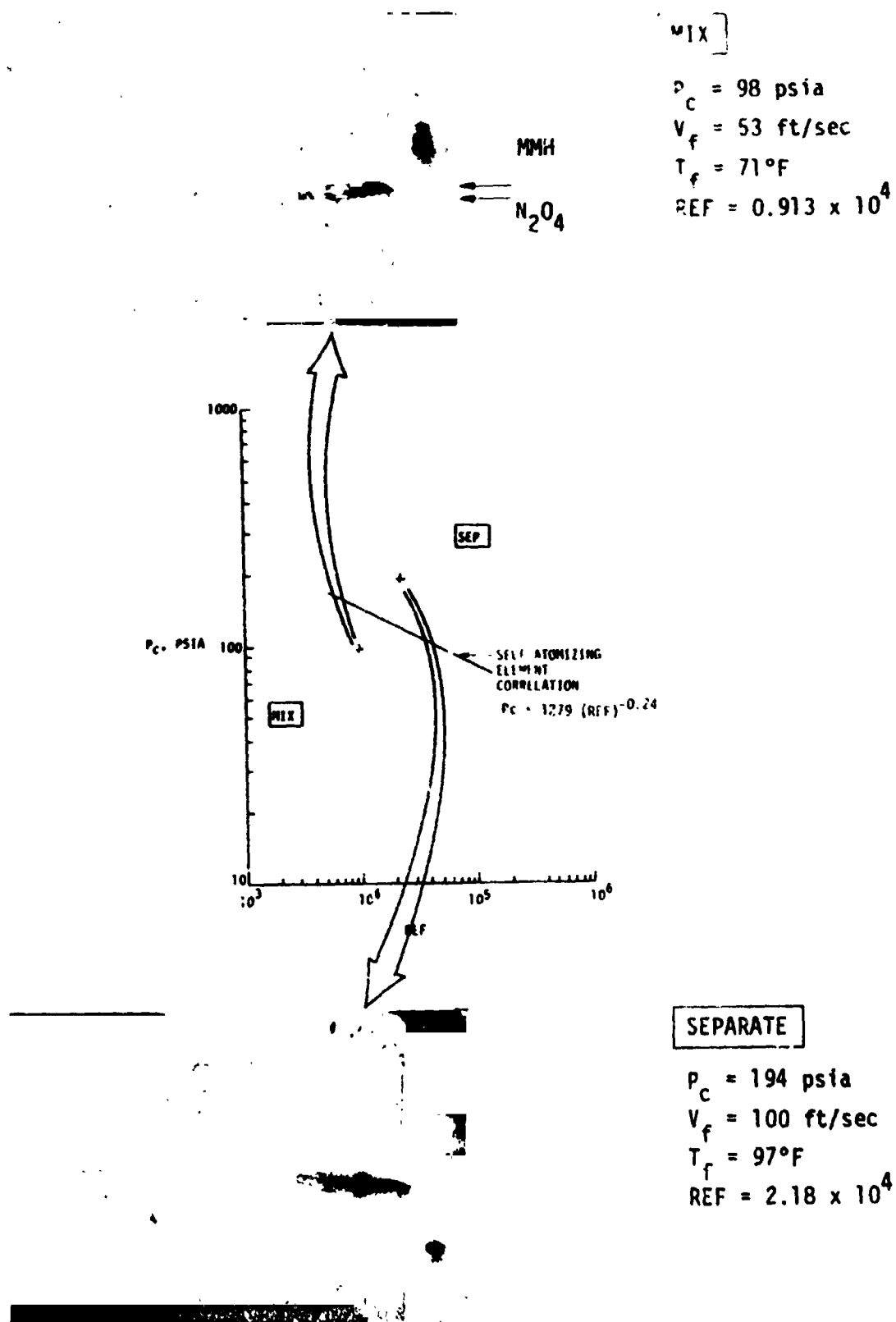
Figure 39. Reactive Stream Impingement with the XDT Platelet
Element No. 10

SPLASH PLATE PLATELET ELEMENT

$D_f = 0.021$ in.

MMH

N_2O_4

$\boxed{MIX}$

$P_c = 102$ psia

$V_f = 48$ ft/sec

$T_f = 72°F$

REF $= 0.844 \times 10^4$

$\boxed{SEP}$

SELF ATOMIZING
ELEMENT
CORRELATION

$P_c = 1272 \, (REF)^{-0.24}$

$\boxed{MIX}$

P_c, PSIA

REF

$\boxed{\text{SEPARATE}}$

$P_c = 186$ psia

$V_f = 104$ ft/sec

$T_f = 79°F$

REF $= 1.94 \times 10^4$
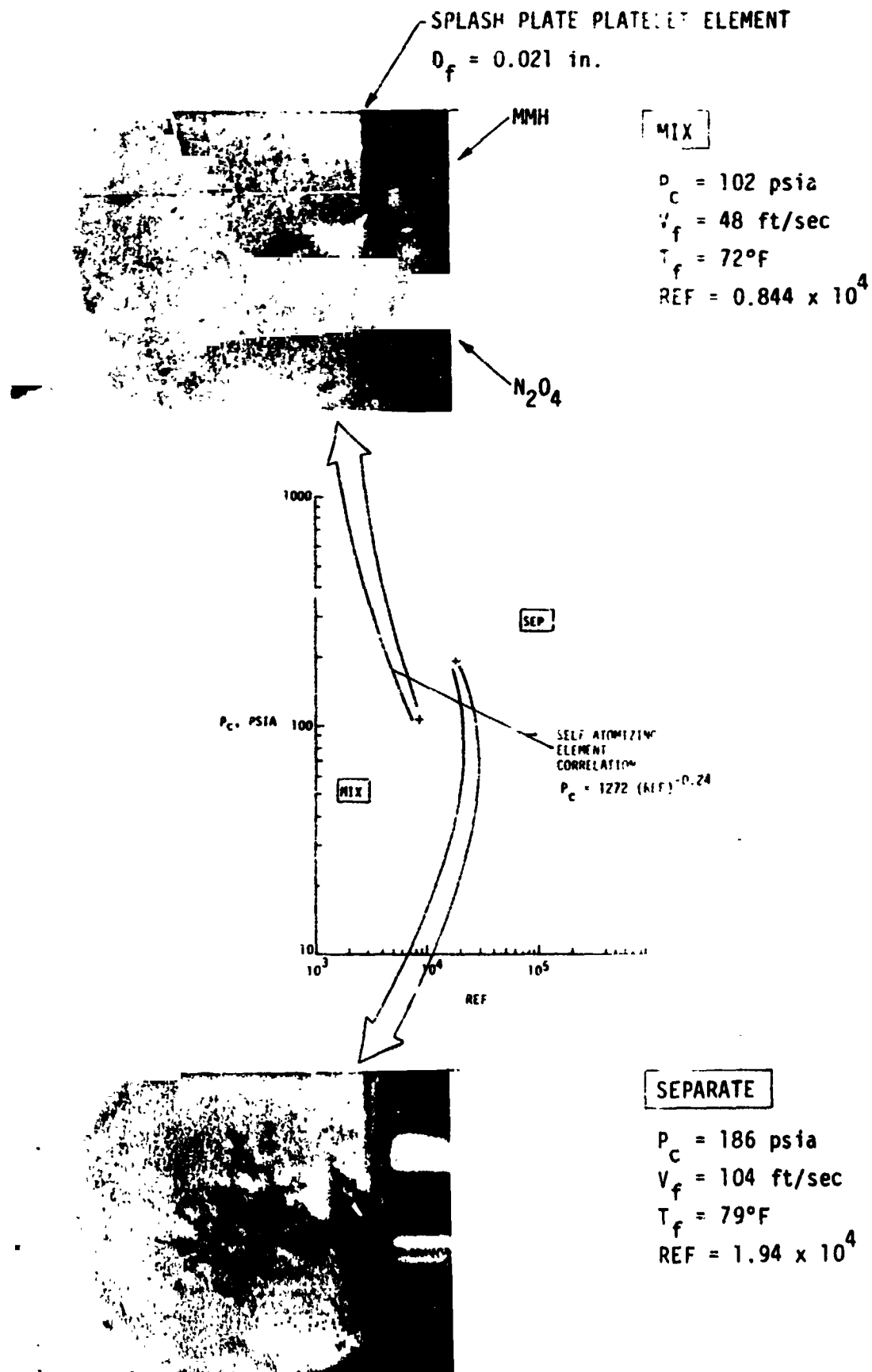
Figure 40.   Reactive Stream Impingement with the Splash-Plate
             Element No. 11

MMH

N_2O_4

SEPARATE
P_c = 140 psia
V_f = 73 ft/sec
T_f = 220°F
REF = 4.81 x 10⁴
MR = 1.61

SEPARATE
P_c = 132 psia
V_f = 74 ft/sec
T_f = 226°F
REF = 5.07 x 10⁴
MR = 1.47

SEPARATE
P_c = 131 psia
V_f = 64 ft/sec
T_f = 218°F
REF = 4.16 x 10⁴
MR = 1.81

SEPARATE
P_c = 110 psia
V_f = 65 ft/sec
T_f = 226°F
REF = 4.42 x 10⁴
MR = 1.46

SEPARATE
P_c = 113 psia
V_f = 56 ft/sec
T_f = 214°F
REF = 3.53 x 10⁴
MR = 1.80

ORIGINAL PAGE IS
OF POOR QUALITY

SEPARATE
P_c = 103 psia
V_f = 54 ft/sec
T_f = 217°F
REF = 3.52 x 10⁴
MR = 1.65

Figure 41.   Reactive Stream Impingement with the Space Shuttle/
OMS TLOL Platelet Element No. 9

78

SPACE SHUTTLE/OMS
TLOL ELEMENT
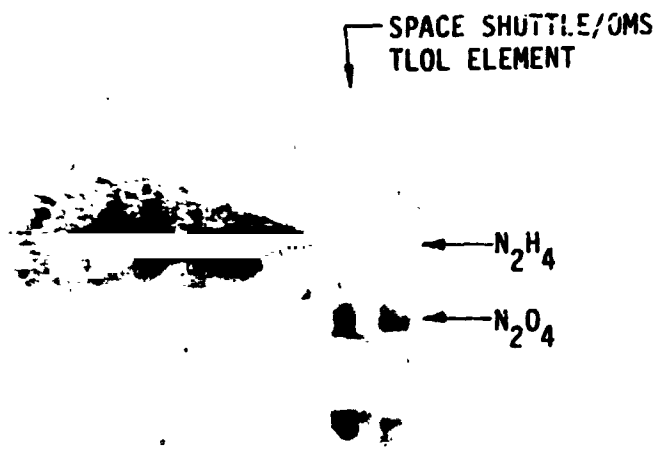
SEPARATE

P_c = 110 psia
V_f = 91 ft/sec
T_f = 150°R
REF = 3.5 x 10^4
MR = 1.65
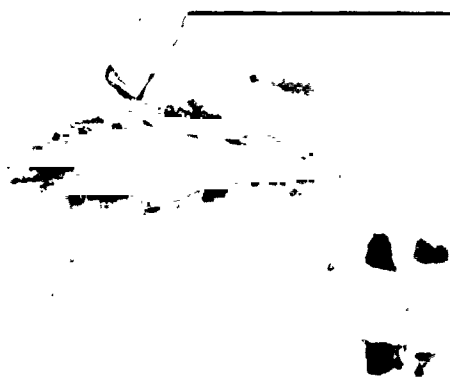
N_2H_4
N_2O_4

SEPARATE

P_c = 137 psia
V_f = 119 ft/sec
T_f = 152°F
REF - 4.63 x 10^4
MR = 1.62
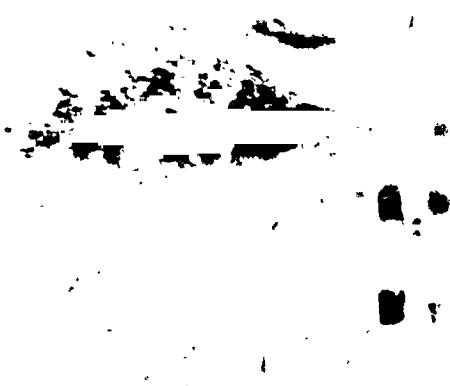
SEPARATE

P_c = 206 psia
V_f = 78 ft/sec
T_f = 78°F
REF = 1.86 x 10^4
MR = 1.67

Figure 42. Reactive Stream Impingement with the Space Shuttle/
OMS TLOL Platelet Element Using N_2H_4 Fuel

VI, Technical Discussion (cont.)

D.   RSS MODEL DEVELOPMENT

The approach taken to develop an understanding of the RSS
mechanisms which led to the vaporization controlled model is outlined in
Figure 3. The process involved literature review, model evaluation,
development of high speed color photography techniques, testing of single
elements, and analytical modeling. Each of these efforts are discussed in
a chronological development.

An evaluation of existing RSS models and development of
RSS correlations was accomplished during the proposal effort and are reported
in the Task I Data Dump (Ref. 18). The results showed that the existing
models were inadequate and that the mechanisms controlling RSS were not
understood. The data correlations, developed using the Zung (Ref. 17)
N_2O_4/N_2H_4 data, showed that the controlling design parameters were chamber
pressure, fuel temperature and fuel orifice diameter as illustrated in
Figure 43. The data defined a low pressure and a high pressure regime
of RSS. The low pressure RSS is clearly due to flash vaporization of the
N_2O_4 when it is injected in a supersaturated condition. Low pressure RSS
is of less significance to the engine designer than the high pressure
RSS since it is generally not encountered at normal engine operating
pressures.

The possible modes of hypergolic reactions were examined
for possible RSS mechanisms since the cause of high pressure RSS was not
obvious. Possible mechanisms were postulated for the various regimes
on the basis of this examination. It was found that hypergolic reactions
occur primarily in the gas phase. Liquid phase reactions are not possible
(Ref. 14) due to extreme reactivity and immicibility of these propellants.
However, reactions do take place on the fuel surface under certain conditions
(Refs. 26 and 27). These surface reactions lead to incomplete low enthalpy
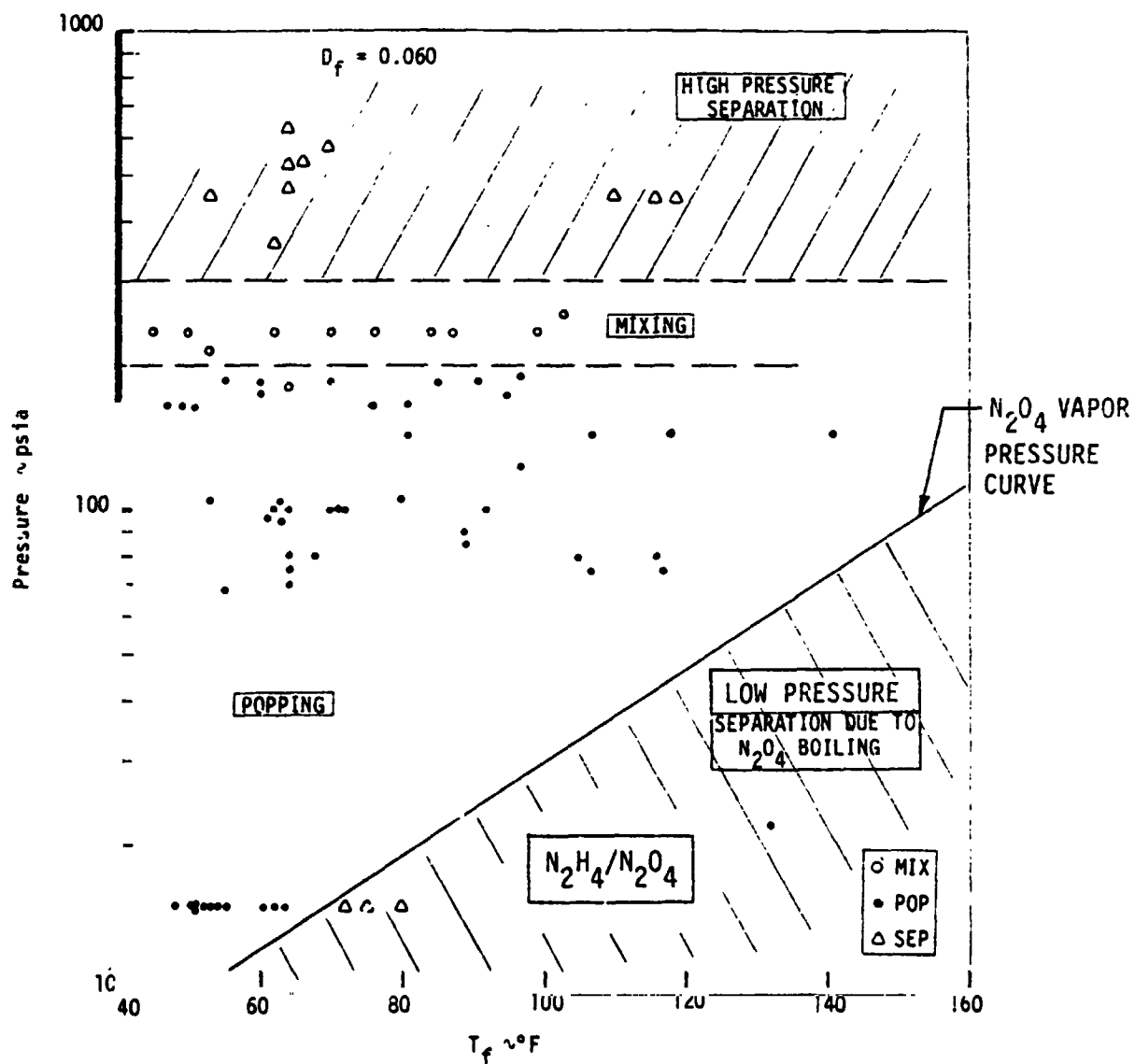
Figure 43. Task I RSS Data Correlations

combustion with the generation of solid reaction intermediates. The gas phase reactions can occur in both a bipropellant and a mono-propellant mode.

High pressure RSS was postulated to be a result of mono-propellant decomposition of the fuel ahead of impingement due to hot gas recirculation heating as shown in Figure 44. It was believed that the recirculation gas heats the fuel to the saturation temperature as shown in Figure 44, with RSS occurring when the saturation temperature exceeds the fuel vapor decomposition temperature ($\sim$450°F). The monopropellant decomposition model predicted different chamber pressure limit for the Amine fuels depending on their vapor pressure as shown in Figure 44. However, the measured chamber pressure limits were subsequently found to be much lower and to depend on fuel velocity and temperature.

Analyses conducted during Task I indicated that significant heating of the bulk fuel stream does not occur although the surface film is rapidly heated to the saturation temperature. The two rounded inlet unlike injector elements shown in Figure 7 were designed to map RSS and to test the high pressure RSS model during Task III. One element was designed with a longer impingement length and, hence, more free stream heating than the other to test the recirculation gas heating effect on the monopropellant decomposition model.

The results of the Task III testing showed that the impingement length (i.e., recirculation gas heating) had no effect on RSS for the range of lengths tested. It was also found that the RSS limits did not agree with those predicted for MMH and A-50 fuels, therefore, it was concluded that the proposed model was not correct. These test results also showed that the transition from the mixed mode to the separated mode occurs

82
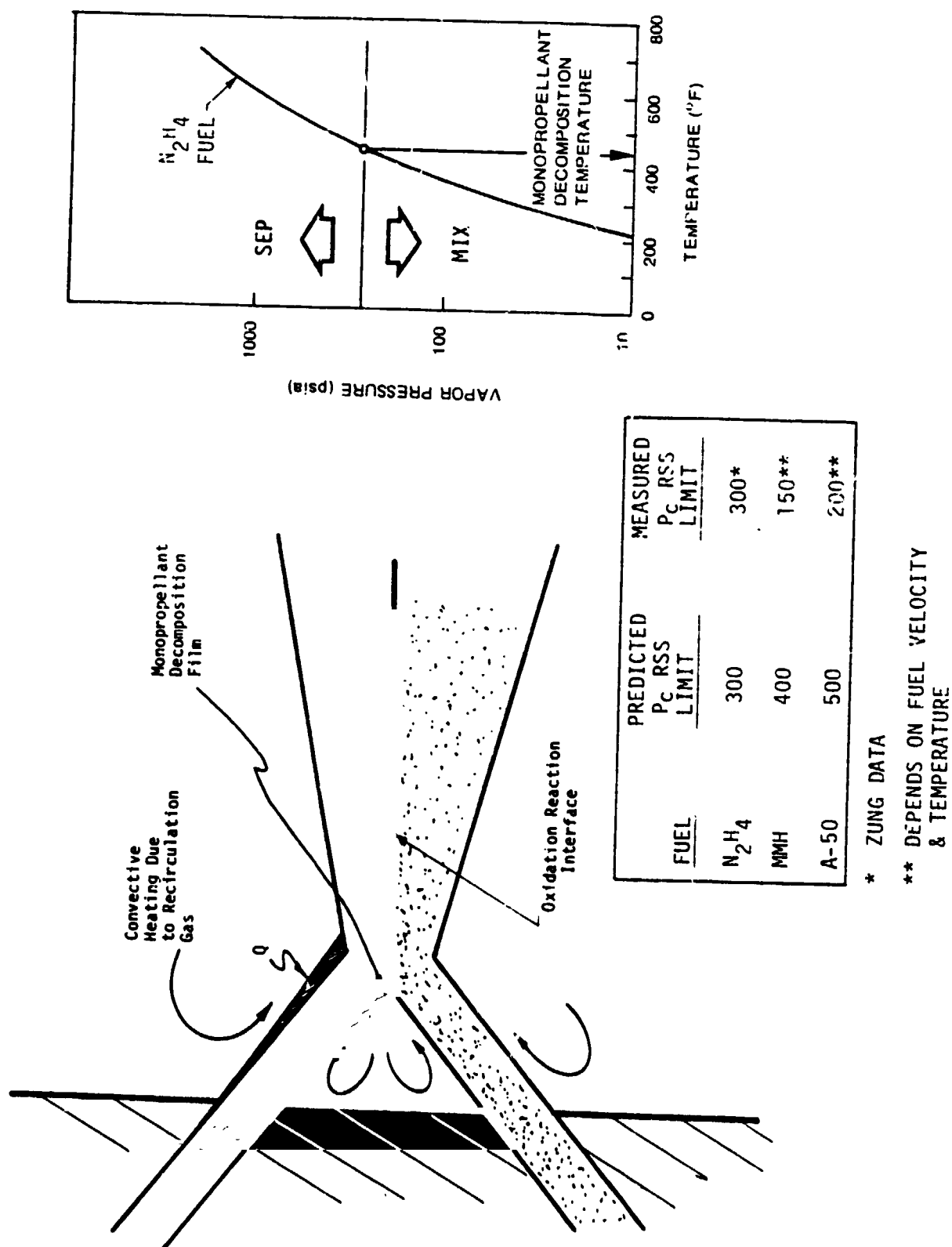
Figure 44. High Pressure Monopropellant Decomposition RSS Model

gradually with increasing chamber pressure rather than with an abrupt
change as had been previously supposed. An injection velocity and fuel
temperature effect on high pressure RSS was observed which was not indi-
cated by the proposal and Task I data correlations.

Impingement point temperature probing with small diameter
thermocouples and close examination of the movie film led to the develop-
ment of a surface reaction controlled RSS model aimed at explaining the
velocity effect. It was observed that aerodynamic shedding of liquid drop-
lets from the fuel jet surface occurs when the fuel velocity exceeds a
certain value identified by a critical Weber Number as shown in Figure 45.
Because the impingement point temperature rise was found to increase with
Weber Number (i.e., injection velocity and chamber pressure) it was postu-
lated that RSS is controlled by a surface reaction. It was reasoned that
increasing the Weber Number would increase the pre-impingement surface area
due to droplet sheeding and hence promote RSS.

The vapor phase reaction model shown in Figure 46 was
derived in an attempt to explain the observed fuel temperature effect.
It was postulated that the gas phase reactivity could be related to the
vapor phase mixture ratio (MRVP). The MRVP decreases from extremely
oxidizer rich values with ambient temperature fuel to near stoichiometric
values when the fuel is heated. Hence, it as reasoned that increasing
fuel temperature would increase reactivity and promote RSS. The rounded
inlet unlike doublet data were correlated by plotting the fuel Weber
Number versus the MRVP as shown in Figure 47. Although the correlation
showed promise for the rounded inlet unlike doublet it was found to be
unsatisfactory for some of the other elements. A more generally applicable
correlation is provided by the chamber pressure and fuel Reynolds Number.

LIQUID STREAM

GASEOUS ATMOSPHERE

D_l

ρg

V_l

$W_e < W_{e_{critical}}$

DROPLET SHEDDING

ρ_g

V_l

$W_e > W_{e_{critical}}$

W_e = AERODYNAMIC SURFACE FORCE / SURFACE TENSION

$$W_e = \frac{\rho_g \, \Delta V_l^2 \, D_l}{\sigma_l \, g_c}$$

$$W_{e_{crit}} = 12 \left[1 + \left(\frac{\mu_l^2}{\rho_l \, D_l \, \sigma_l \, g} \right)^{0.36} \right]$$

$\rho_g = \dfrac{P_c}{R_c T_c}$ = COMBUSTION GAS DENSITY

P_c = CHAMBER PRESSURE

R_c = COMBUSTION GAS CONSTANT

T_c = COMBUSTION GAS TEMPERATURE

Figure 45. Weber Number Model

Control
Volume

Ox

Fuel

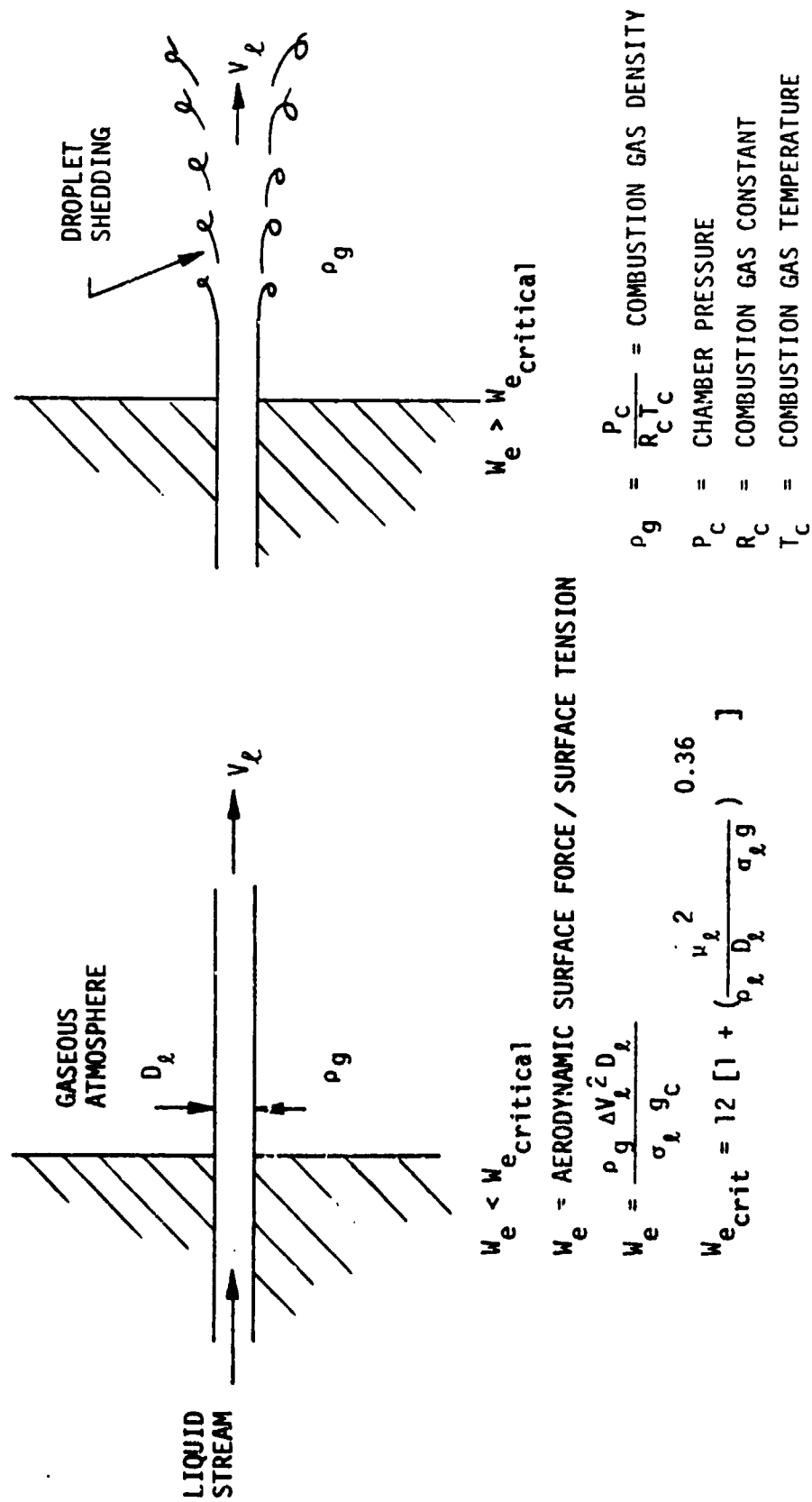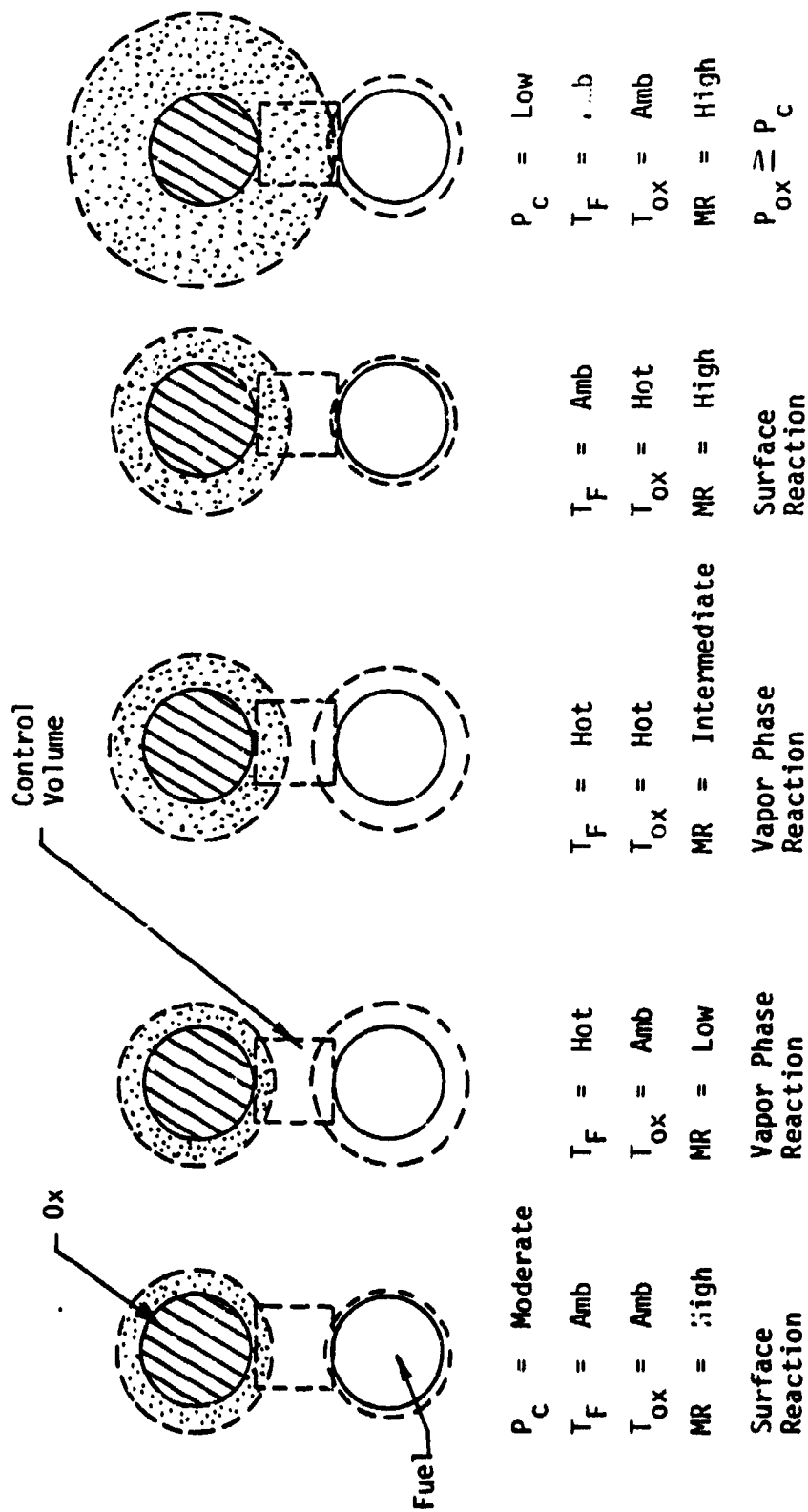|					
P_c = Moderate	P_c =				P_c = Low
T_F = Amb	T_F = Hot	T_F = Hot	T_F = Amb		T_F = Amb
T_{ox} = Amb	T_{ox} = Amb	T_{ox} = Hot	T_{ox} = Hot		T_{ox} = Amb
MR = High	MR = Low	MR = Intermediate	MR = High		MR = High
Surface Reaction	Vapor Phase Reaction	Vapor Phase Reaction	Surface Reaction		$P_{ox} \geq P_c$

$$MR_{vp} = 2.0 \; \frac{p_{ox}}{p_f} \; \frac{T_f}{T_{ox}}$$

Figure 46. Vapor Phase Reaction Model

86
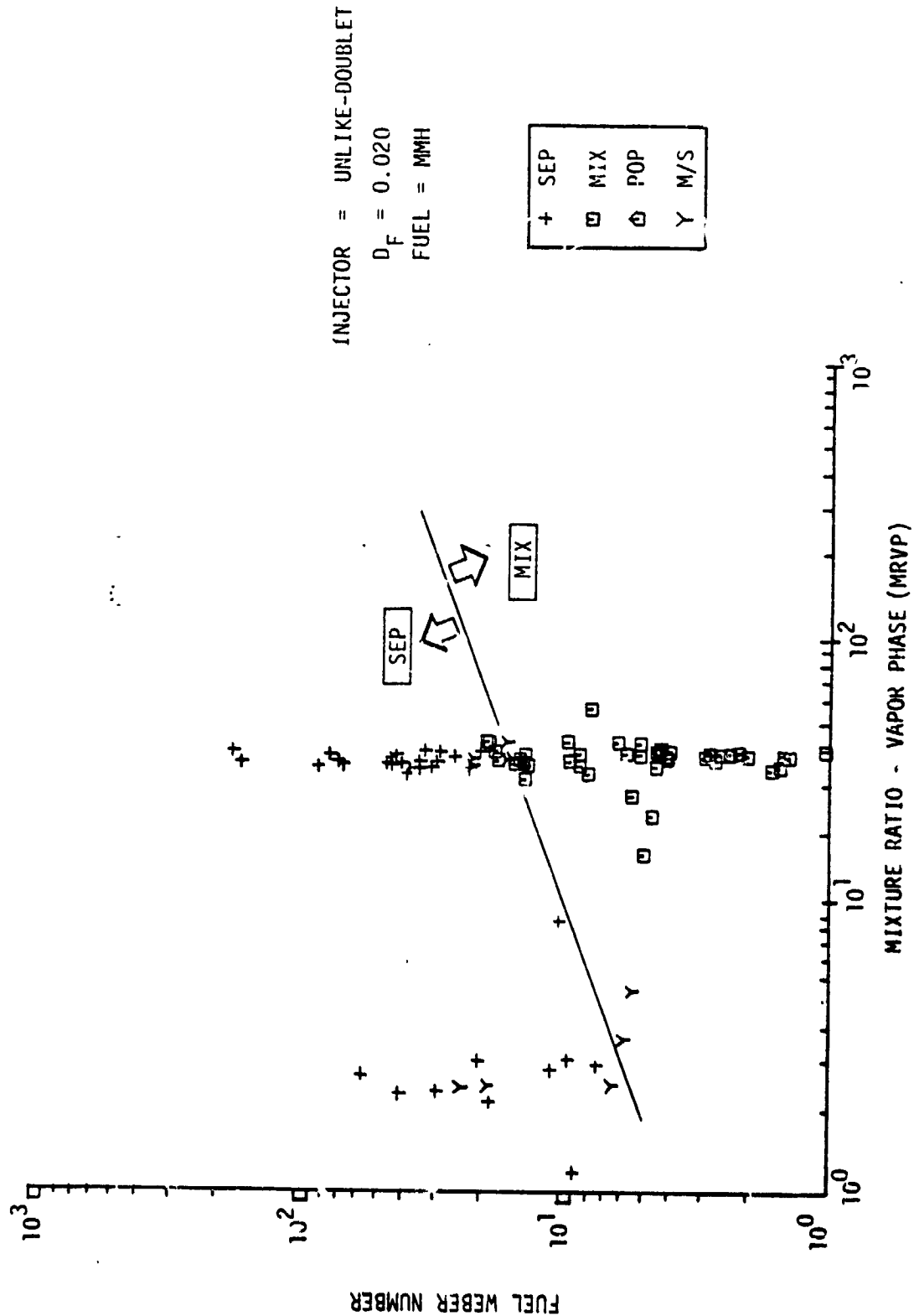
Figure 47. Fuel Weber Number and MRVP RSS Correlation

87

VI, D, RSS Model Development (cont.)

Task IV included testing of the small and large F-O-F triplet elements and the XDT and splash plate self-atomizing impingement type of injectors to test the influence of increased interfacial surface area on RSS. Hot firing confirmed that self-atomizing injector elements promote RSS due to increased interfacial surface area. Cold flow experiments were also made shich showed that jet shedding with coherent streams could be correlated with Reynolds Number as well as with Weber Number. This led to development of the final data correlations during Task V. I' was found that RSS could be correlated for both coherent stream injectors and self-atomizing injectors by plotting chamber pressure versus fuel Reynolds Number as shown in Figures 4 and 5. The vaporization controlled RSS model outlined in Figure 48 resulted from the Task V effort.

Testing during Task VII was done to, (1) verify the vaporization controlled RCS model using the sharp edged unlike doublet flight type injector elements and, (2) to characterize the Space Shuttle OMS engine and RCS engine injector elements over their respective operating ranges. The results show that RSS with flight type injectors correlate with the vaporization model using either MMH or N_2H_4 fuel indicating the validity of the RSS model.

The strong RSS dependence on chamber pressure and fuel Reynolds Number can be related to a fuel vaporization rate controlled combustion mechanism by making the following assumptions:

1.   The combustion gas generation rate prior to and at the impingement interface must exceed some minimum rate for RSS to occur.

2.   Combustion gas generation occurs through gas phase reaction only.

88

C-2

JET SHEDDING OR SELF ATOMIZATION

D_f

V_f

RSS

FUEL VAPORIZATION SURFACE AREA - A_S

GAS PHASE REACTION OF PROPELLANT VAPORS

VAPOR/DROPLET MANTEL

A-A
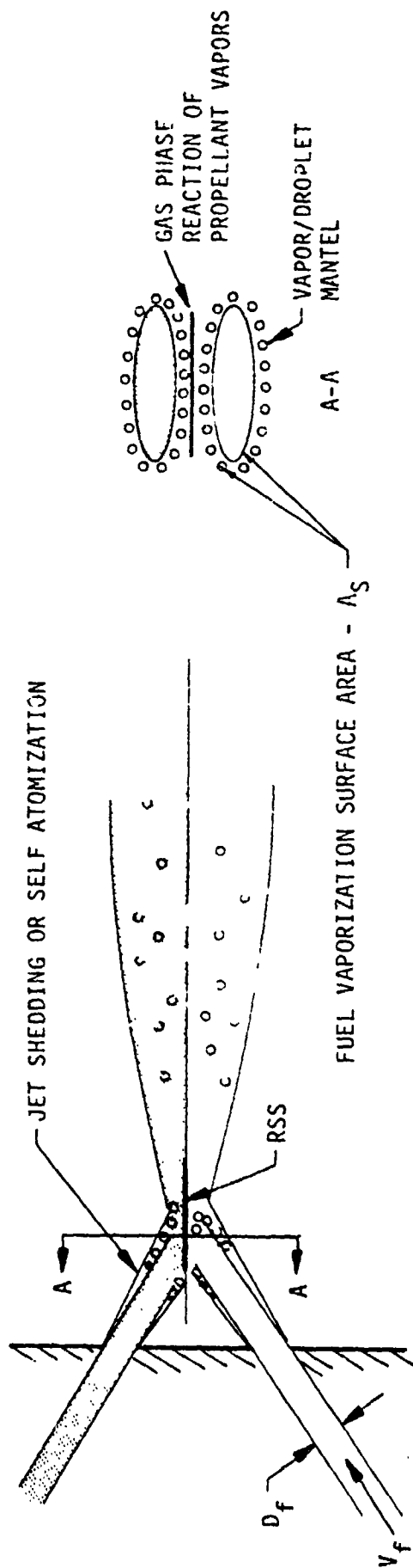
VAPORIZATION RATE:

$\dot{W}_V = A_S K_V P_{VS} = A_S K_V P_C$

$\dot{W}_V$ = VAPORIZATION RATE

A_S = EVAPORATION SURFACE AREA

K_V = MASS TRANSFER COEFFICIENT

P_{VS} = FUEL VAPOR PRESSURE EVALUATED AT T_{SAT}

P_C = CHAMBER PRESSURE

MASS TRANSFER COEFFICIENT:

$Nu_m = D_S R T K_V / \mathcal{D} = 2.0 + 0.6 \ Sc^{1/3} Re^{1/2}$

D_S = DROPLET DIAMETER

R = GAS CONSTANT

T = FILM TEMPERATURE

$\mathcal{D}$ = DIFFUSION COEFFICIENT

ASSUMPTIONS:

• COMBUSTION GAS GENERATION RATE MUST EXCEED SOME MINIMUM RATE FOR RSS TO OCCUR

• COMBUSTION GAS GENERATION OCCURS THROUGH GAS PHASE REACTION ONLY

• COMBUSTION GAS GENERATION RATE IS LIMITED BY VAPORIZATION RATE FROM FUEL VAPORIZATION SURFACE AREA

• FUEL FILM IS HEATED TO SATURATION TEMPERATURE

JET IMPINGEMENT: $P_C \propto Re^{-3/2}$

$A_S \propto Re$

SELF ATOMIZING IMPINGEMENT: $P_C \propto Re^{-1/2}$

$A_S \neq f(Re)$

Figure 48. Fuel Vaporization Controlled RSS Model

VI, D, RSS Model Development (cont.)

3. Combustion gas generation rate is limited by the fuel preimpingement vaporization rate since it is the more difficult propellant to vaporize.

The vaporization rate is related to the fuel vapor pressure and vaporization surface area through the mass transfer equation (Ref. 28):

$$\dot{W}_v = A_s \, K_v \, P_v \qquad \text{Equation (3)}$$

where:

$\dot{W}_v$ = evaporation rate

A_s = fuel vaporization surface area

K_w = mass transfer coefficient

P_v = fuel vapor pressure

The fuel vaporization surface area includes all fuel vaporizing surfaces ahead of impingement. This includes the jet surface and droplet surfaces as shown in Figure 48.

From the movie film and the Task I analysis it is apparent that the surface of the fuel stream is rapidly heated to the saturation temperature such that the vapor pressure is essentially equal to the chamber pressure. Therefore,

$$\dot{W}_v = A_s \, K_v \, P_c \qquad \text{Equation (4)}$$

where:

$P_v = P_c$, at·the saturation temperature

P_c = chamber pressure

The mass transfer coefficient (K_v) is related to the Nusselt Number for mass t.ansfer.

$$Nu_m = \frac{D_s \, R \, T \, K_v}{\mathcal{B}} \qquad \text{Equation (5)}$$

90

VI, D, RSS Model Development (cont.)

where:

D_s = droplet diameter

R = gas constant

T = average film temperature

$\mathcal{D}$ = diffusion coefficient

The evaporation constant can be related to the Reynolds Number through the Ranz and Marshall Nusselt number correlation for evaporation (Ref. 29):

$$Nu_m = 2.0 + 0.6\ Sc^{1/3}\ REF^{1/2} \qquad \text{Equation (6)}$$

where:

S_c = Schmidt Number

REF = Fuel Reynolds Number

The evaporation constant can be expressed in terms of the Reynolds Number by combining Equations (5) and (6). The critical fuel vaporization rate and, hence, chamber pressure at which RSS will occur then becomes a function primarily of the surface area for evaporization and the Reynolds Number;

$$\dot{W}_{v_{Critical}} \propto A_s\ f\ (REF^{1/2})\ P_{c_{Critical}} \qquad \text{Equation (7)}$$

$$P_{c_{Critical}} \propto A_s^{-1}\ REF^{-1/2} \qquad \text{Equation (8)}$$

It is known that the pre-impingement surface area is velocity or Reynolds Number dependent for coherent streams such as those produced by drilled or EDM'ed orifices with L/D's greater than about 4/1. Whereas, the pre-impingement surface area for self-atomizing injectors is only weakly

91

VI, D, RSS Model Development (cont.)

dependent on the velocity or Reynolds number. Therefore, the critical
chamber pressure for coherent streams is expected to be more dependent
on Reynolds number than the self-atomizing injector elements:

Rounded Inlet $P_{c_{Critical}} \propto REF^{-3/2}$ Equation (9)
Unlike Doublets

where:

$A_s \propto REF$

Self-Atomizing $P_{c_{Critical}} \propto REF^{-1/2}$ Equation (10)
Elements

where:

$A_s \neq f(REF)$

This model shows good agreement with the coherent stream
experimental data in that the measured exponent on REF is equal to -3/2. The
exponent on REF is found to be -0.24 rather than -0.5 for the self-
atomizing elements. However, the agreement with the experimental data is
sufficient to conclude that RSS is controlled primarily by fuel vapori-
zation rate controlled combustion.

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94

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APPENDIX A

HYPERGOLIC PROPELLANT
INJECTOR ELEMENT DESIGN CRITERIA

Appendix A

HYPERGOLIC PROPELLANT
INJECTOR ELEMENT DESIGN CRITERIA

Prepared by:

B. R. Lawver

March 1979

Appendix A

TABLE OF CONTENTS

LIST OF TABLES

iii

Appendix A

LIST OF FIGURES

Appendix A

I. INTRODUCTION

The objective of this document is to present injector element design
criteria that will aid an injector designer in understanding, avoiding, and
coping with hypergolic propellants that result in Reactive Stream Separation
(RSS) or reduced mixing of the oxidizer and fuel streams.

The liquid rocket engine combustion process is discussed at the outset
to establish a frame of reference for the RSS design criteria. A discussion
of non-reactive stream impingement phenomena is included to lay the ground
work for understanding the influence of reactive stream phenomena on the
impingement mixing process. This discussion is followed by a description
of reactive stream phenomena illustrated with photographs. Data correlations
are provided for coherent stream and atomized spray impingement injector
element configurations which define regimes of reactive stream separation.
Finally, reactive impingement design criteria are presented which enable
the designer to predict regimes of RSS for his particular design and
operating conditions.

The reactive impingement design criteria specified herein are applic-
able to the N_2O_4 oxidizer and Amine fuels propellant combinations. The
criteria are limited to elements with fuel orifice diameters of 0.030 inches
or less. The following design and operating ranges are applicable:

> Chamber Pressure   = 80 - 1000 psia
> Fuel Velocity   = 25 - 200 ft/sec
> Oxidizer Velocity   = 25 - 150 ft/sec
> Fuel Temperature   = 50 - 300°F
> Oxidizer Temperature = 50 - 160°F .

These criteria deal only with the optimization of the intra-element mixing
processes. Other criteria required to achieve high performance, stability,
and compatibility are not included.

1

Appendix A

II.   LIQUID ROCKET COMBUSTION PROCESS

Liquid propellant rocket engine combustion represents a multi-faceted problem. It includes the following phenomenological processes as illustrated in Figure 1.

- °   Liquid stream injection
- °   Stream impingement and spray formation
- °   Propellant atomization
- °   Unlike propellant droplet mixing
- °   Droplet vaporization
- °   Vapor phase mixing
- °   Chemical reaction
- °   Combustion gas mixing
- °   Nozzle expansion

Engine performance is limited by the combustion and gas dynamic losses listed in Figure 1. The achievement of high performance requires that these performance losses be held to a minimum. It is generally recognized that the mixing loss associated with injector generated mixture ratio non-uniformities is the largest loss the injector designer has to deal with. The mass and mixture ratio uniformity which defines the mixing loss, is determined by the injector design and the impingement mixing process as illustrated in Figure 1. Therefore, the goal of any injector design is to produce uniform, stable, reproducible propellant mass and mixture ratio distributions. This goal is best achieved through an understanding of the physico-chemical mechanisms controlling the mixing process.

The injector promotes mixing through intra-element (within the element) and inter-element (element-to-element) mixing. Understanding the intra-element mixing process is key to injector design since pattern layout requires that the element distributions be known so that inter-element mixing can be optimized. Propellant distribution uniformity is

● Injector   ● Vaporization
  Hydraulics   ● Vapor Phase Mixing
                     ● Combustion Gas Mixing
● Atomization

Downstream Mass & Mixture Ratio
is Controlled by Impingement Process

● Stream   ● Spray Droplet   ● Nozzle Expansion
  Impingement   Mixing   ● Chemical Kinetics
● Spray Formation   ● Boundary Layer Loss

● Propellant Mixing Influeces
  Combustion Chamber
      Specific Impulse
      Gas-Side Heat Transfer
      Stability
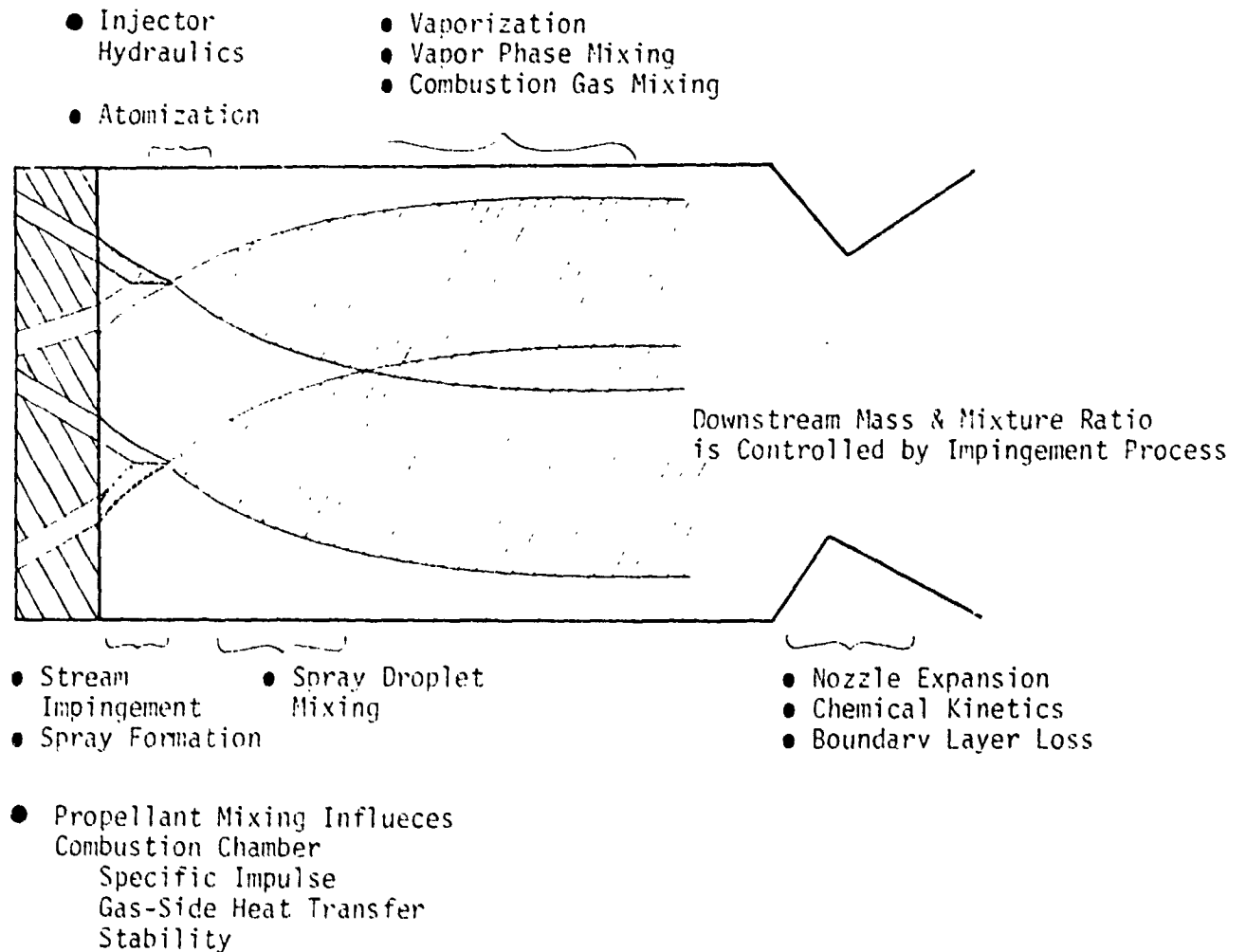
Figure 1.   Impingement Point Processes Impact Propellant Mixing

II, Liquid Rocket Combustion Process (cont.)

achieved primarily through intra-element and inter-element liquid/droplet
momentum exchange processes since downstream gas phase mixing is too slow
to achieve the required mixing. Since impingement point spray mixing
controls the spray mass and mixture ratio distributions, any injection or
combustion process that inhibits or modifies the intra-element spray
mixing process will impact performance, gas side heat transfer response
and stability. Reactive Stream Separation (RSS) is a combustion related
phenomena that exhibits this influence. However, there are also non-
reactive related phenomena such as "hydraulic flip", momentum imbalance,
and diameter mismatch that can impact the spray distributions which also
need to be considered. Thus, high performance injector design criteria
must include both reactive (hot fire) and non-reactive (cold flow) impinge-
ment phenomena effects upon the intra-element mixing process.

Intra-element mixing is generally achieved by momentum exchange
through impingement of coherent streams or atomized sprays. Coherent
streams are produced by drilled or electrical discharge machined (EDM)
orifices. Atomized propellant sprays are produced by like impingement
of coherent streams or by self-atomization using splash plates or
platelet injector elements. Platelet injectors are fabricated by bonding
together a stack of thin metal sheets which have etched flow passages.
The Space Shuttle/RCS (SS/RCS) Engine injector shown in Figure 2 is an example
of a coherent stream impingement injector element. Whereas the Space
Shuttle/OMS (SS/OMS) Engine injector shown in Figure 3 is an example of the
atomized spray impingement type of injector. Non-reactive and reactive
impingement processes are discussed for both class of injectors.

4

FUEL
INLET

OXIDIZER
INLET

NOTE:
DIMENSIONS IN
INCHES.

ORIGINAL PAGE IS
OF POOR QUALITY
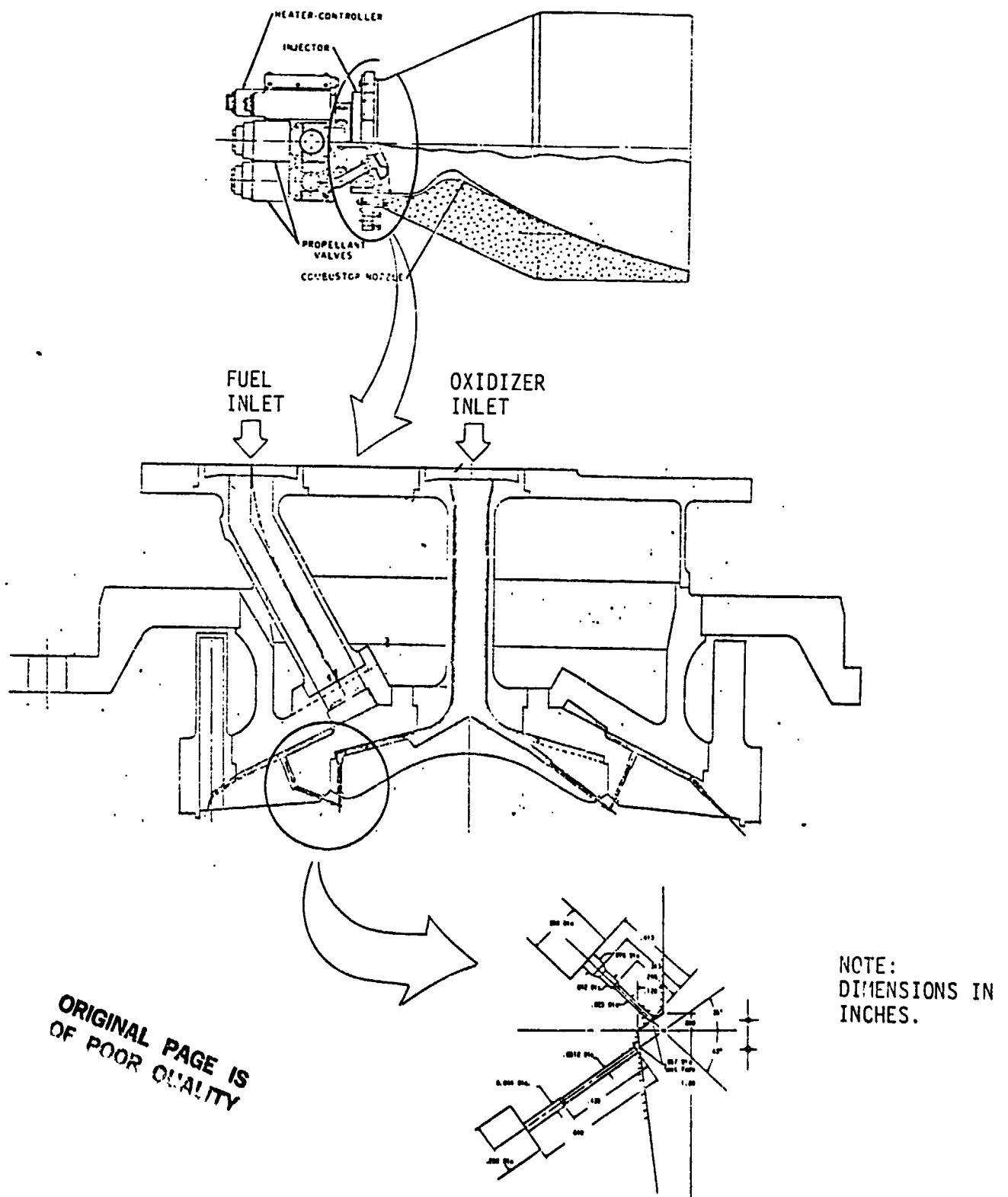
Figure 2.   Space Shuttle/RCS Engine Injector

FUEL DISTRIBUTION
INLET (FROM REGEN.
CHAMBER)

OX INLET

PLATELET
ASSY.

16 FACE
RING
CHANNELS

OX MANIFOLD

FUEL MANIFOLD

TRANSVERSE PLATELET

FUEL

SECONDARY
IMPINGEMENT
POINT

₵ OF
LAND

OX

ORIFICE ELEMENT
(2 PLACES)

METERING
ELEMENT

FACE #1

FACE #2

F

O

FUEL
.028

OX
.032

Figure 3.   Space Shuttle/OMS Engine Injector

Appendix A

III.   NON-REACTIVE STREAM IMPINGEMENT PHENOMENA

Non-reactive stream impingement phenomena which can effect spray distribution with coherent stream impingement include, "hydraulic flip", momentum imbalance, diameter mismatch and stream quality. The impingement phenomena observed with sprays depends on the method used to produce the sprays. For example, sprays produced by self-impingement of coherent jets are susceptible to the same processes as the coherent streams. Whereas, sprays produced by impingement with surfaces generally are not subject to "hydraulic flip" since these streams generally are made to flow detached. These non-reactive phenomena are discussed in detail for each class of injector below.

A.   COHERENT STREAM IMPINGEMENT

The preponderance of operational hypergolic propellant engines use coherent stream impingement to produce intra-element mixing. Rupe and his co-workers (Ref. 1, 2 and 3) were the first to recognize the importance of intra-element mixing upon injector performance. They expended considerable effort to develop empirical spray mass and mixture ratio distribution correlations based on cold flow data for engine design application. Rupe recognized early in these investigations that hydraulic stability is essential to efficient mixing. Rupe's work is the most definitive and widely used non-reactive injector design criteria.

The non-reactive coherent stream impingement mixing process is illustrated in the photographs of Figure 4. These photographs are enlargements of single frames taken from 16 mm high speed movie film. The injector is a rounded inlet unlike doublet used on the N_2O_4/Amine Fuels Program (NAS 9-14186). The propellant simulants are dyed water (the blue stream) for fuel and freon (the clear stream) for oxidizer. Rupe's mixing uniformity criteria is equal to 1.0 for optimum mixing. The spray uniformity
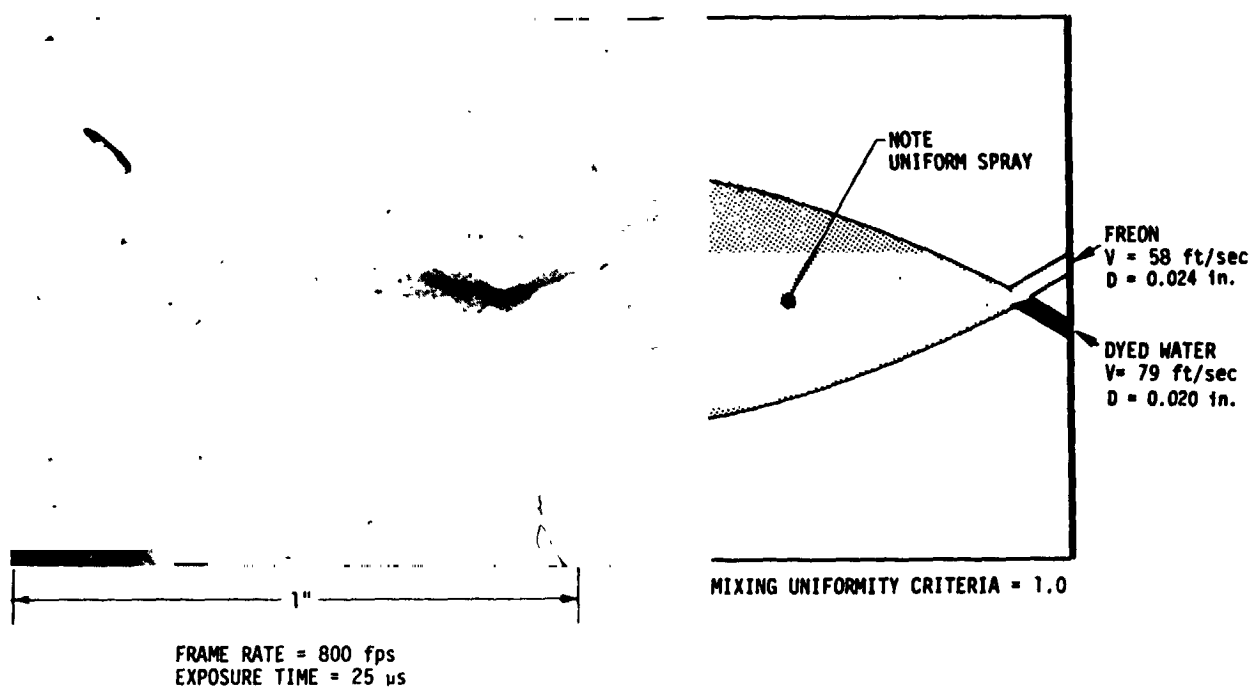
MIXING UNIFORMITY CRITERIA = 1.0

FRAME RATE = 800 fps
EXPOSURE TIME = 25 µs

a.   Rupe's Mixing Uniformity Criteria Defines Uniform Spray for Non-reactive Impingement

MIXING UNIFORMITY CRITERIA = 0.9

FRAME RATE = 800 fps
EXPOSURE TIME = 25 µsec
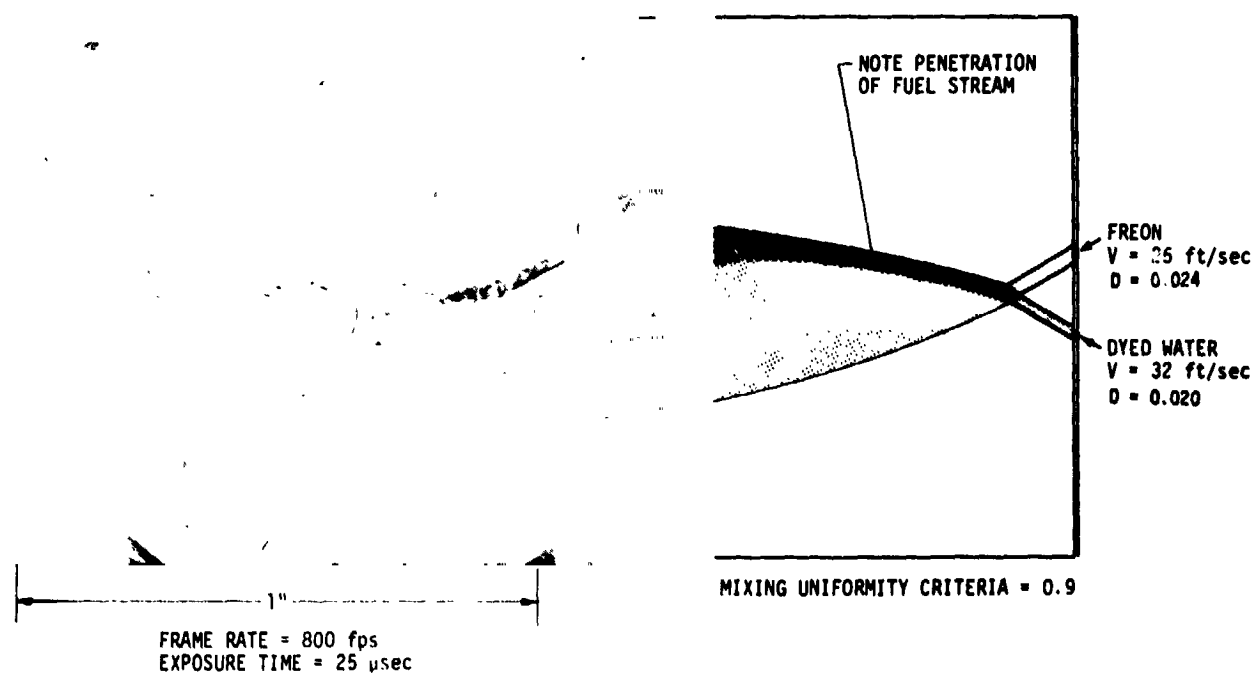
b.   Low Stream Momentum Produces Penetration Phenomena for Non-reactive Impingement

Figure 4.   Rupe's Mixing Uniformity Criteria Defines Uniform Spray
for Non-Reactive Impingement

Appendix A

III, A, Coherent Stream Impingement (cont.)

attained at the optimum stream momentum ratio condition, in the absence
of combustion, is clearly evident in the upper photograph. The propel-
lant "shoot-through" (i.e., penetration) phenomena reported by Rupe is
also observed with lower stream momentums as shown in the lower photo-
graph of Figure 4.

Non-reactive phenomena which can alter this spray uniformity
are:

1. Fuel/Oxidizer Diameter Mismatch
2. Fuel/Oxidizer Momentum Imbalance
3. Stream Instability   -
4. Stream Quality
5. Impingement Misalignment

Each of these phenomena must be considered in designing coherent stream
injectors.

1. **Fuel/Oxidizer Diameter Mismatch**

Rupe placed most of his emphasis upon investigating the
unlike doublet element to chracterize element mixing efficiencies. He
found that equal fuel and oxidizer injection momentums and equal orifice
diameters are required to maximize unlike doublet mixing efficiencies.
However, the only commonly used propellant combination which satisfies
both criteria is N_2O_4/N_2H_4. In most cases, the oxidizer injection momentum
exceeds that of the fuel causing the oxidizer orifice diameter to be
larger than that of the fuel. A slight diameter mismatch results in under
penetration of the fuel jet into the higher momentum oxidizer stream
causing reduced mixing efficiencies. Large diameter mismatches result in
skewed spray distributions as illustrated in Figure 5.

9
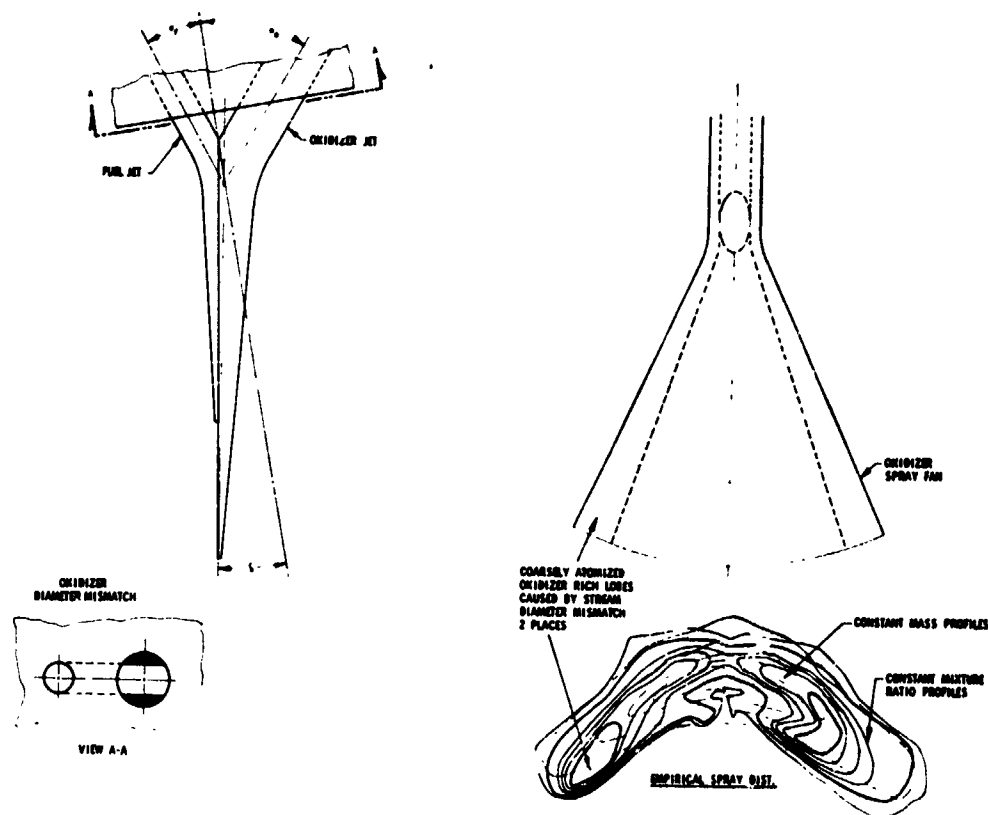
Appendix A

a. Measured Spray Distribution
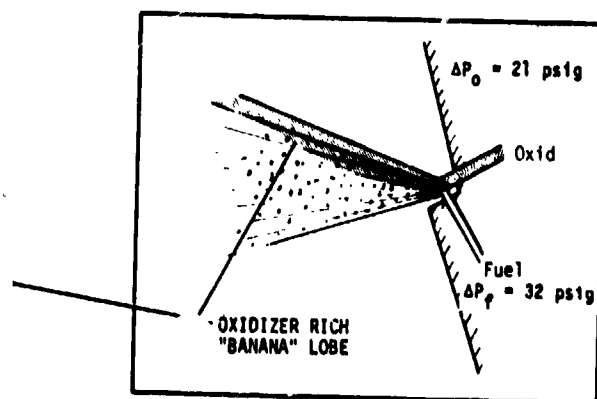
b. Visual Evidence of Diameter Mismatch Effect

Figure 5. Diameter Mismatch Produced "Banana" Shaped Mass
and Mixture Ratio Distribution

III, A, Coherent Stream Impingement (cont.)

Figure 5a displays the results of an experimentally measured spray distribution obtained with unequal diameter circular unlike doublet orifices using non-reactive propellant simulants. The large orifice diameter mismatch produces a "banana" shaped spray distribution which results in two poorly atomized, poorly mixed, oxidizer rich lobes emanating from the misimpingement cross section caused by the diameter mismatch. The diameter mismatch phenomena is further illustrated in Figure 5b. This stroboscopic still photo was taken of cold flow tests of a single element injector which simulates the Space Shuttle/RCS engine unlike doublet. The propellant simulants are water for fuel and oxidizer.

The problem of diameter mismatch can be alleviated either through the use of EDM'ed rectangular orifices (Ref. 4) or through the use of multiple orifice impingement elements such as the triplet or pentad. EDM'ed unlike doublets with rectangular cross section can be selected with equal element widths to eliminate jet diameter mismatch effects normally associated with circular orifice injectors. This non-circular orifice capability permits a greater degree of freedom in designing impinging coherent stream injectors. It is especially beneficial for those propellant combinations which normally operate at oxidizer to fuel mixture ratios, momentum ratios, and orifice area ratios between 1.0 to 2.0. This includes the important storable propellant combinations of N_2O_4/MMH and N_2O_4/A-50 used on many current engines.

2. Fuel/Oxidizer Momentum Imbalance

Rupe performed extensive studies to define the influence of stream momentum on the spray distribution uniformity. The results are shown in Figure 6 for several unlike doublet elements. The spray uniformity drops off as the momentum balance moves to either side of the optimum value.

11
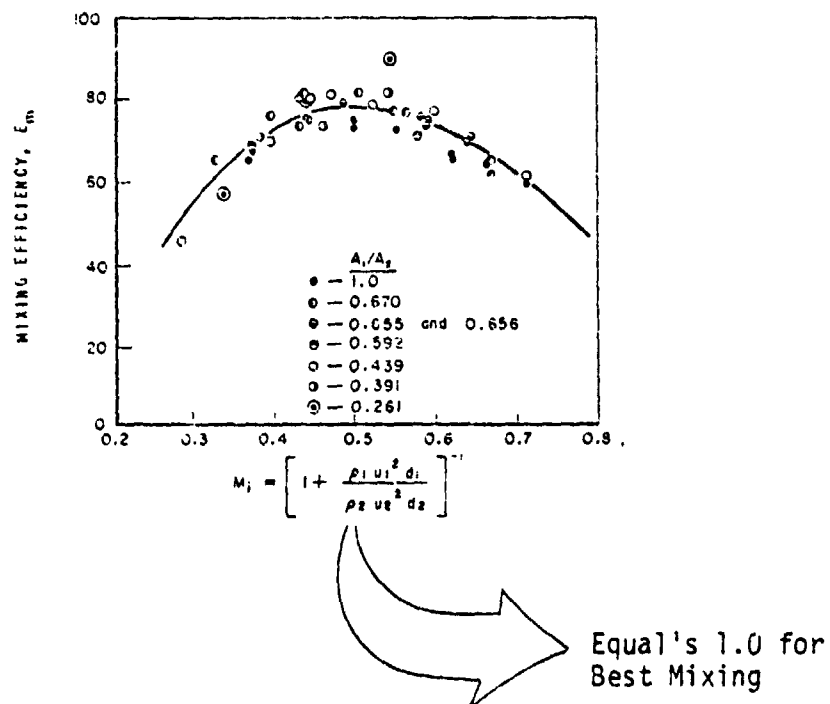
Figure 6. Mixing Uniformity Criteria Defines Best Mixing
Momentum Ratio

Appendix A

III, A, Coherent Stream Impingement (cont.)

On the basis of these data, Rupe developed a spray mixing
uniformity criteria for unlike impinging doublet propellant streams. The
mixing uniformity criteria (Ref. 2) states that optimum spray mixing occurs
when the product of the ratios of the velocity heads and stream diameters
is equal to unity:

$$\rho_{ox} V_{ox}^2 D_{ox}/\rho_f V_f^2 D_f = 1.0 \qquad \text{Equation (1)}$$

Similar mixing correlations were developed by Elverum and Morey (Ref. 3)
for other types of impinging injector elements using Rupe's cold flow
measurement techniques. These correlations are summarized in Table I for
unlike jet impingement elements.
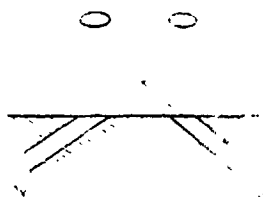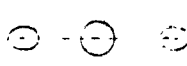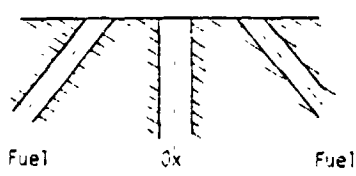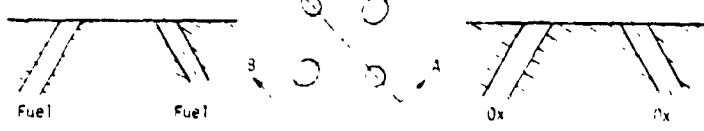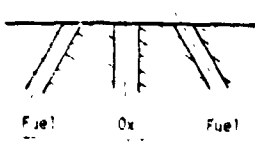
Operation at an oxidizer rich off-momentum conditions is
illustrated in Figure 7 for the SS/RCS unlike doublet element. The resultant
spray momentum angle is drastically changed in addition to modifying the intra-
element mixing. Changes in spray momentum angle can seriously impact chamber
gas-side heat transfer response and combustion stability. The sensitivity of
spray momentum angle to momentum balance can be alleviated through the use of
multiple impingement elements such as the triplet or pentad.

The fuel rich off-momentum condition is also illustrated
in Figure 7 for the SS/RCS unlike doublet. The low oxidizer momentum and
diameter mismatch cause the oxidizer stream to "umbrella" around the fuel
stream resulting in poor mixing. These effects coupled with RSS can result
in undesirable performance, stability, and compatibility variability over
the engine operating range.

Appendix A

TABLE I

NON-REACTIVE SPRAY MIXING CRITERIA FOR HYDRAULICALLY STABLE UNLIKE IMPINGING JETS

ELEMENT NAME	DESIGN CHARACTERISTIC	MIXING OPTIMIZATION DESIGN CRITERION

Unlike Doublet (One-on-One)

$$\left(\frac{\dot{W}_{ox}}{\dot{W}_f}\right) \times \left(\frac{V_{ox}}{V_f}\right) = \frac{D_{ox}}{D_f}$$

Inline Triplet (Two-on-One)

$$\left(\frac{\dot{W}_f}{\dot{W}_{ox}}\right)^2 \frac{\rho_{ox}}{\rho_f} \left(\frac{A_{ox}}{2 A_f}\right)^{1.75} = .66$$

$$(2\theta_f = 60 \text{ degrees})$$

or

$$\frac{\rho_f V_f^2}{\rho_{ox} V_{ox}^2} \left(\frac{2 A_f}{A_{ox}}\right)^{0.25} = .42$$

$$(2\theta_f = 90 \text{ degrees})$$

Trans Quadlet (Two-on-Two)

Same as Unlike Doublet, or

$$\left(\frac{\dot{W}_{ox}}{\dot{W}_f}\right)^2 \frac{\rho_f}{\rho_{ox}} \left(\frac{D_f}{D_{ox}}\right)^3 = 1.0$$

A-A   B-B

Pentad (Four-on-One)

$$\left(\frac{\dot{W}_f}{\dot{W}_{ox}}\right)^2 \frac{\rho_{ox}}{\rho_f} \left(\frac{A_{ox}}{4 A_f}\right)^{1.25} = 2.75$$

Fuel   Ox   Fuel
A-A

Correlations from Ref. (3)

$\dot{W}_f$ = Fuel Flowrate (lb/sec)
$\dot{W}_{ox}$ = Oxidizer Flowrate (lb/sec)
ρ_f = Fuel Density (lb/ft³)
ρ_{ox} = Oxidizer Density (lb/ft³)
A_f = Fuel Orifice area (in.²)
A_{ox} = Oxidizer Orifice Area (in.²)

a. Orifice Diameter Mismatch Produces Non-Uniform Spray
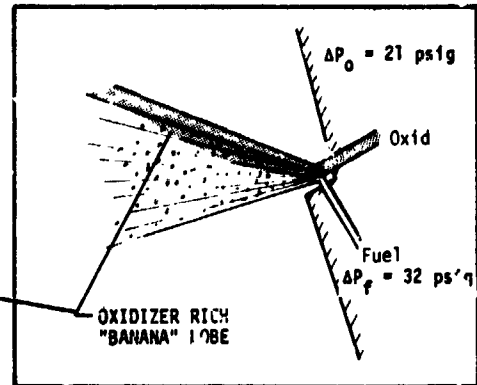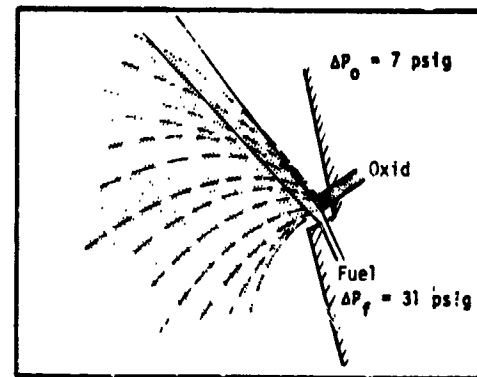
b. Fuel Rich Momentum Condition Causes Oxidizer Stream to "Umbrella" Around Fuel Stream
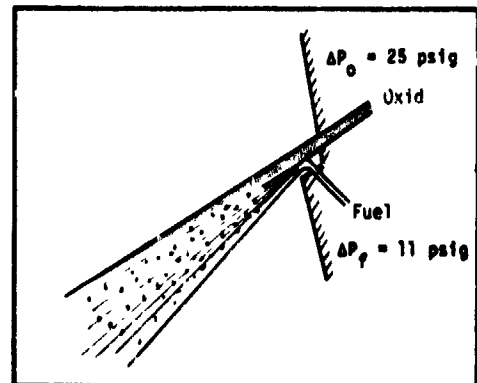
c. Oxidizer Rich Momentum Condition Produces Good Mixing

Figure 7. Momentum Ratio Imbalance Significantly Modifies
Intra-element Mixing

Appendix A

III, A, Coherent Stream Impingement (cont.)

3. Stream Stability

Rupe stresses the importance of stream stability throughout his work. Stream stability is controlled primarily by the orifice geometry. The orifice configurations that are most commonly used in rocket injectors are illustrated in Figure 8. The features of each are as follows: (a) represents the conventional sharp edged orifice, (b) is a rounded or contour approach orifice, (c) is a higher L/D, square-edged orifice, which produced a cylindrical jet as in (a) and (b), while (d) is that same orifice where the jet has reattached to the orifice wall, and (e) is the same as (d) but with a longer L/D.

For the sharp-edged orifice flow conditions of (a) and (c) the discharge coefficient C_d lies between 0.6 and 0.7. In (d), the flow reattaches to the wall allowing the orifice to flow "full". The result is agitated and divergent flow at the exit (bush or broomy flow), and the discharge coefficient rises to between 0.8 and 0.85. The bushy flow disappears as the orifice length is increased as in (e). A still higher C_d ($\approx$ 0.97) is achieved with (b) when the contour is not too abrupt and L/D is small (0.25 to 0.5). For the best designs C_d = 0.99, while with poor curvature and high manifold cross velocities the discharge coefficient may be as low as 0.90.

Early rocket injector designs were dominated by the configuration exemplified by (c) and (d) and hence are characterized by the flow properties just described. The transition between flow condition (c) and (d) is known as "hydraulic flip" and is sensitive to chamber pressure, orifice length/diameter ratio, orifice entrance configuration, and the fluid properties. The "hydraulic flip" is accompanied by a change in pressure drop as illustrated in Figure 9 and a change in stream quality from

16

L/D < 0.5 ——— (a)

L/D ≥ 0.25 ——— (b)

L/D = 1-2 ——— (c)

L/D = 2-4 ——— (d)

L/D > 4 ——— (e)
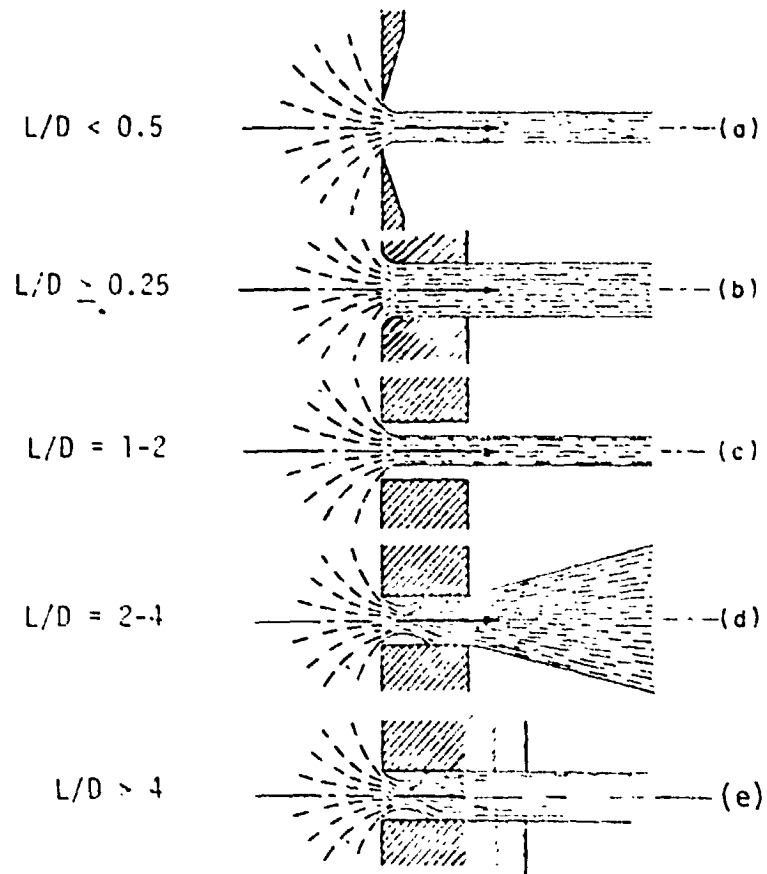
Figure 8. Injector Stream Characteristics Depend on Orifice Configuration
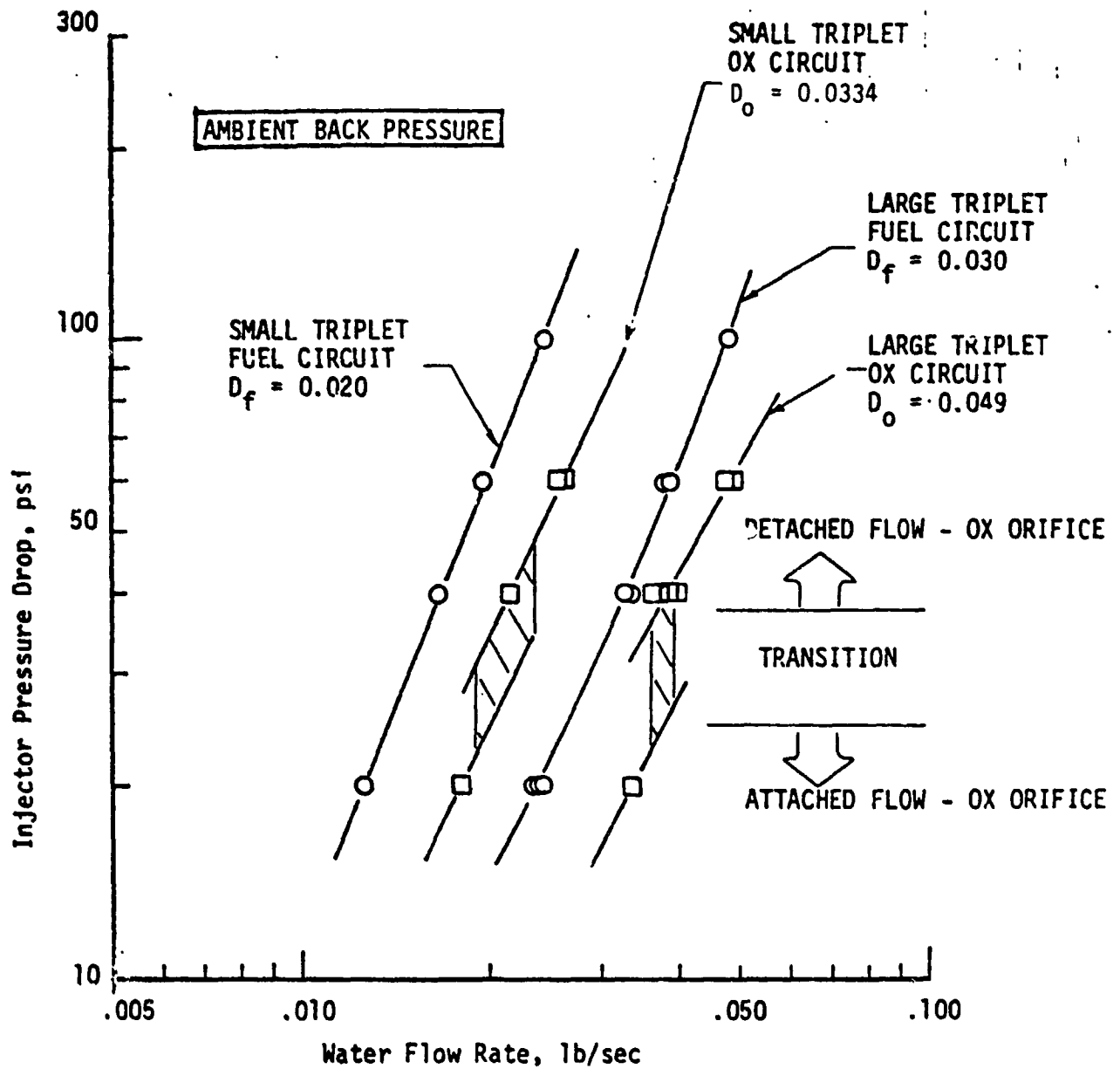
Figure 9. Hydraulic Flip Modifies Pressure Drop and Stream Quality

Appendix A

III, A, Coherent Stream Impingement (cont.)

coherent to bushy streams which impacts the spray mixing. Reference 5
describes the phenomenon of hydraulic flip in detail which occurs due to
abrupt transitions between attached and detached flow in sharp edge orifices
caused by either fluid cavitation or insufficient L/D. Stable, predictable
orifice discharge coefficients free of hydraulic flip are necessary not only
to obtain predictable orifice pressure drop and desired injection momentum
ratios, but also to obtain maximum cold flow mixing efficiency.

Contoured inlet orifices provide the most stable and
optimum injection mass distribution, however, the orifice inlets are fre-
quently inaccessible for contouring and the designer has little or no
choice other than to use sharp edge inlet orifices. Although orifice L/D
ratios $\geq$ 2:1 usually flow attached for most applications, jet directional
flow control is often poor. Combinations of high manifold cross velocity,
low orifice static pressure drop and nonperpendicular orifice orientation
to the manifold backside surface cause angular deviations between the
injected stream and orifice axis unless the sharp edge orifice L/D $\geq$ 4:1.
Unless unlike jet impingement occurs right at the surface of the injector
face, directional flow control is an important consideration for assuring
desired impingement characteristics. Directional flow control becomes
increasingly critical for coherent jets as the distance from the orifice
exit to the unlike impingement point increases.

With the advent of EDM, most modern injector designs are
exemplified by configuration (e) which generally provide stable well
defined streams.

19

Appendix A

III, A, Coherent Stream Impingement (cont.)

4. Stream Quality

A stream's quality is defined by its velocity profile and degree of pre-atomization. A high quality stream is one having a nearly uniform velocity profile and a coherent non-bushy appearance. Rupe's work (Refs. 1 and 2) shows that the intra-element mixing efficiency and reproducibility are highly dependent on stream quality. The stream velocity profile is determined primarily by the orifice configuration (Ref. 4) whereas bushiness or preatomization is influenced by both the orifice configuration and the fluid velocity.

The contoured inlet orifices and long L/D ($\sim$ 100) orifices such as those used by Rupe produce nearly flat velocity profiles and are required for maximum intra-element mixing efficiency. The velocity profile reflects the fraction of the fluid contained within the velocity boundary layer relative to the potential flow core. For contoured orifice inlets and/or long L/D orifices such as those used by Rupe, the mass in the boundary layer is very small and jet shedding is minimized. Likewise short L/D sharp edge orifices which flow detached from the vena contracta to the exit likewise have low mass in the velocity boundary layer and exhibit minimal shedding. A more detailed description of inlet contraction coefficient effects, Reynolds number and L/D effects upon exit velocity profile, static pressure recovery efficiency and element discharge coefficient is given in Reference 5.

The mechamism of droplet shedding from the jet surface prior to impingement is shown schematically in Figure 10. This pre-impingement shedding is caused by shear forces induced within the jet boundary layer. The onset of pre-impingement aerodynamic atomization is modeled through the Weber Number which is a function of the injection

20

GASEOUS ATMOSPHERE

LIQUID STREAM

D_ℓ

ρ_g

V_ℓ

$W_e < W_{e_{critical}}$

W_e = AERODYNAMIC SURFACE FORCE / SURFACE TENSION

$$W_e = \frac{\rho_g \, \Delta V_\ell^2 \, D_\ell}{\sigma_\ell \, g_c}$$

$$W_{e_{crit}} = 12 \left[1 + \left(\frac{\mu_\ell^2}{\rho_\ell \, D_\ell} \cdot \frac{1}{\sigma_\ell \, g} \right)^{0.36} \right]$$

DROPLET SHEDDING

V_ℓ

ρ_g

$W_e > W_{e_{critical}}$

$\rho_g = \dfrac{P_c}{R_c T_c}$ = COMBUSTION GAS DENSITY

P_c = CHAMBER PRESSURE

R_c = COMBUSTION GAS CONSTANT

T_c = COMBUSTION GAS TEMPERATURE
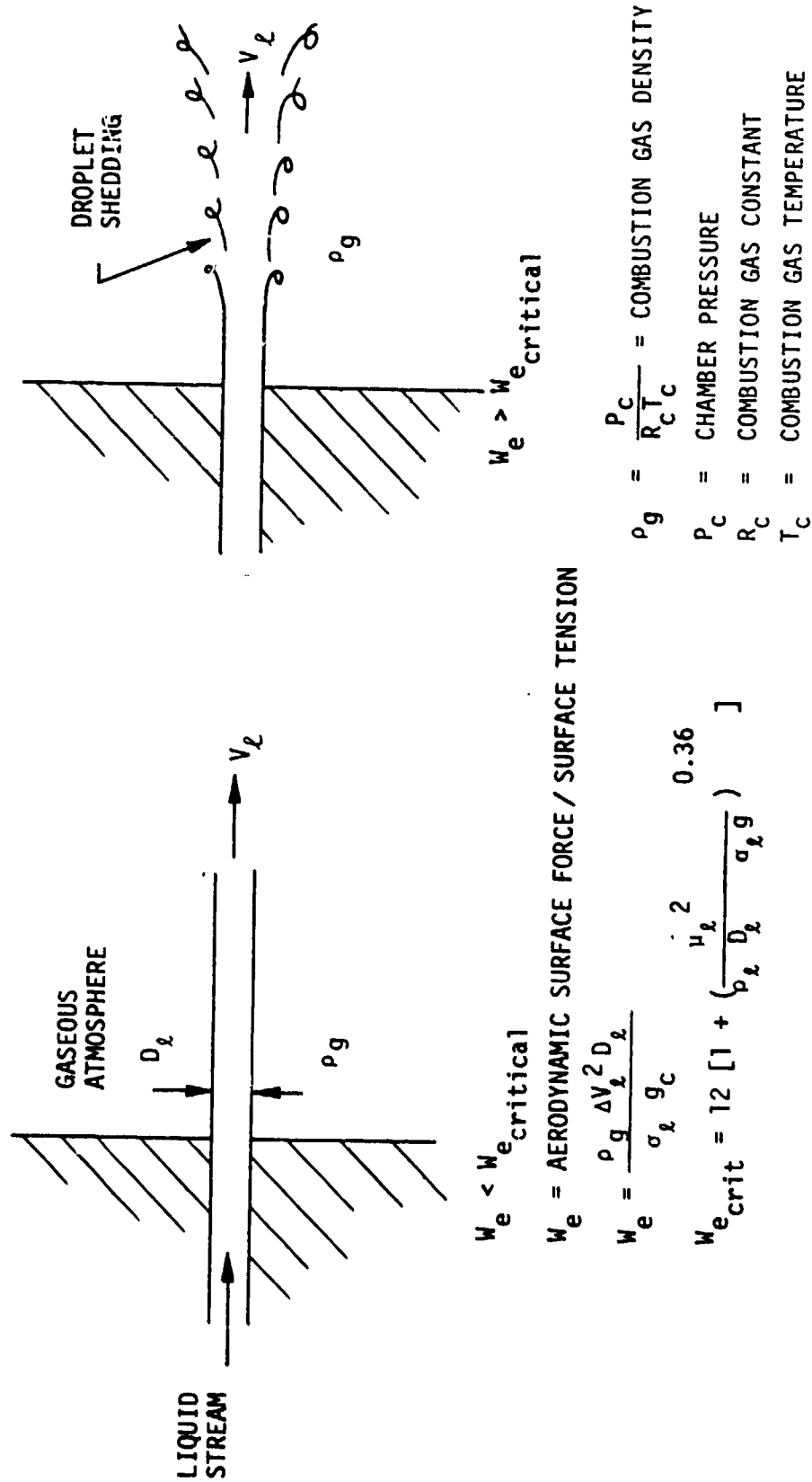
Figure 10. Weber Number Model

III, A, Coherent Stream Impingement (cont.)

velocity, chamber pressure, and fuel surface tension. The Weber Number
is the ratio of aerodynamic shear forces to surface tension forces as
defined in Equation (2):

$$WEF = [\rho_g V_f^2 D_f]/\sigma_f \qquad \text{Equation (2)}$$

Thus the Weber Number (WEF) is a function of the propellant, through the sur-
face tension (σ_f), the chamber pressure through the gas density term (ρ_g),
and the injection process through the stream diameter (D_f) and the injection
velocity (V_f).

A critical Weber Number exists above which the aerodynamic
forces exceed the surface tension force resulting in stream shedding and
atomization. Therefore, the interfacial surface area of streams operating
above the critical Weber Number are greater than that of streams operating
below the critical Weber Number. The increase in pre-impingement atomiza-
tion promotes Reactive Stream Separation because RSS is vaporization con-
trolled and vaporization rate increases as the stream surface area to volume
ratio increases. This surface area increase will also affect the momentum
exchange process.

5. Impingement Misalignment

Impingement misalignment can cause gross changes in the
intra-element mixing as reported by Rupe and co-workers. In addition to the
changes in intra-element mixing, inter-element mixing is impacted due to
rotation of the spray about the spray axis. An example of the impact of
impingement misalignment on the resultant spray is illustrated in Figure 11.
This is a stroboscopic photo of the resultant spray from a simulated LS/RCS
unlike doublet which was intentionally misaligned by offsetting the orifices
by 0.003 inches. The resultant fan rotation and spray nonuniformity are
evident, indicating that impingement misalignment should be avoided.
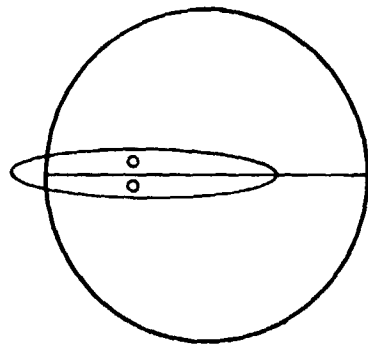
END VIEW   SIDE VIEW

a. NORMAL IMPINGEMENT

$$\Delta P_{ox} = 21 \text{ PSIG}$$
$$\Delta P_f = 32 \text{ PSIG}$$

20°-30°

0.003"
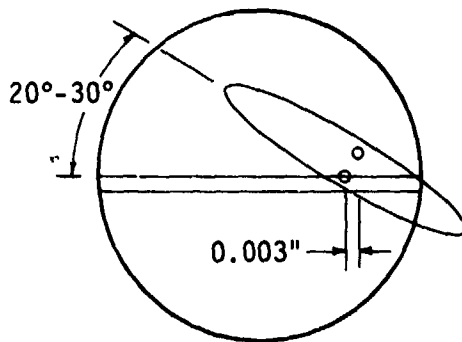
END VIEW

SIDE VIEW

b. OFFSET IMPINGEMENT

Figure 11. Impingement Misalignment Causes Fan Rotation

23

Appendix A

6. Ligament Shedding

Periodic ligament formation and shedding is another cold flow phenomena which also shows up in hot fire testing. The process of ligament formation and shedding is as follows. The ligaments begin to form downstream of the propellant impingement point where the liquid stream begins to spread into a thin sheet. As these ligaments become increasingly large, surface tension forces are overcome causing the ligament to break off and form droplets. Aerodynamic and intertial forces contribute to this atomization process and further the breakdown of the ligaments into fine droplets.

The periodic ligament shedding is clearly visible in still photographs and in the hot fire movies. They appear as semi-circular waves emitting from the impingement point when viewed as shown in Figure 12. The same ligament shedding frequencies are observed in hot fire testing as in cold flow indicating that they are a consequence of the non-reactive atomization process. The atomization frequency is generally proportional to the injection velocity. The atomization rate is an important factor in determining the first longitudinal stability.

B. ATOMIZED SPRAY IMPINGEMENT

Spray impingement to produce intra-element mixing is accomplished by impingement of unlike atomized spray fans produced by like impingement of coherent streams, by solid wall impingement (splash plate elements) or by internally impinged streams with platelet injectors. Prior to the development of the platelet concept the most commonly used atomized spray impingement element was the like-on-like element whose fuel and oxidizer spray fans are radially aligned and canted toward each other.

24
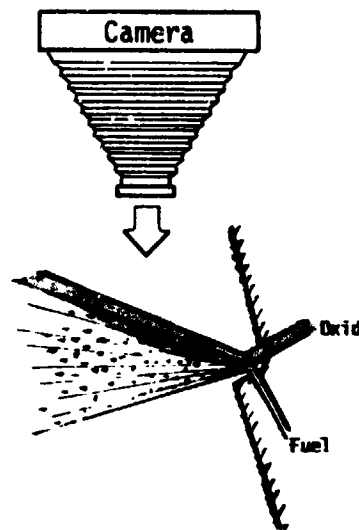
Injector = Space Shuttle/RCS Unlike Doublet
Propellant Simulants = Water
ΔP_0 = 21 psi
ΔP_f = 32 psi
D_0 = 0.031 in.
D_f = 0.023 in.

Figure 12.   Atomization Process Produces Periodic Ligament Shedding

Appendix A

III, B, Atomized Spray Impingement (cont.)

A multitude of atomized spray impingement platelet elements
have been designed and tested at ALRC in recent years. These elements offer
certain advantages in terms of improved producibility. Functionally, their
spray characteristics are similar to any other impinging spray injector.
They produce consistent spray characteristics, predictable atomization
efficiency, and consistent mixing characteristics.

The non-reactive impingement mixing characteristics of the
atomized spray impingement elements are much the same as the coherent
stream elements. Stable orifice flow must be provided to obtain optimum
mixing and the Rupe mixing criteria appears to be applicable.

Spray impingement elements offer two major advantages over the
coherent stream impingement type of elements: (1) alignment between the
oxidizer and fuel orifices is not as critical as with coherent streams since
wide spray fans are impinged compared to narrow streams; and (2) the
spray resultant momentum angle is not as sensitive to momentum imbalance
as with coherent stream impingement.

The principle disadvantages to the spray impingement element
is that the pre-atomization enhances RSS. Another disadvantage is they are
inherently more difficult to fabricate because of increased number of
orifices and compound injection angles. However, this factor can be bene-
ficial for engines that must operate over wide Pc/MR ranges since it
permits operation within the separated RSS regime over the engine entire
operating range. Element overlap is used to avoid performance losses due
to RSS.

Appendix A

IV. REACTIVE STREAM IMPINGEMENT PHENOMENA

Reactive stream impingement can result in Reactive Stream Separation (RSS) which inhibits intra-element momentum mixing. RSS is a consequence of vigorous reaction within the impingement interface which produces combustion gases in sufficient quantities to inhibit liquid stream momentum exchange. The effect of RSS on spray mixing is illustrated in the photographs of Figure 13. Four modes of reactive stream impingement are identified. The first photo in the sequence illustrates the "mix/penetrate" mode which is also observed with non-reactive impingement. The "mix/penetrate" mode is characterized by a uniform spray field with some propellant penetration as evidenced by an oxidizer rich zone opposite the oxidizer stream in the downstream spray. "Penetration" occurs at low injection velocity, (less than 50 ft/sec) low fuel temperatures, (below 70°F) and low chamber pressure (less than 100 psia) and is evidenced by "shot-through" of the fuel and oxidizer. Penetration has been reported in earlier cold flow work and was also observed on this program using propellant simulants as well as reactive streams. Penetration is a consequence of the non-reactive momentum exchange mixing process.

The second photo shows the condition of uniform mixing without evidence of RSS. "Mixing" is observed at moderate injection velocities, (50-100 ft/sec) moderate fuel temperatures, (70-90°F) and moderate chamber pressures (100-200 psia). It is evidenced by a highly uniform spray field which looks similar to a non-reactive spray field. The third photo illustrates the "Mix/Separate" mode which occurs at the onset of RSS. It is evidenced by a slightly non-uniform spray field. The fourth photo shows a condition of highly separated streams (RSS). "Separation" is observed at higher injection velocities (greater than 100 ft/sec), higher fuel temperature, and higher chamber pressures (greater than 200 psia). It is evidenced by highly non-uniform spray fields in which distinct regions of unmixed fuel and oxidizer exist.

PENETRATE

P_c = 78 psia
V_f = 49 ft/sec
T_f = 75°F
REF = 0.832 x 10^4

MIX

P_c = 124 psia
V_f = 73 ft/sec
T_f = 82°F
REF = 1.32 x 10^4

N_2O_4

MMH

ROUNDED INLET UNLIKE
DOUBLET D_f = 0.020 in.
D_o = 0.024 in.

MIX/SEPARATE

P_c = 198 psia
V_f = 114 ft/sec
T_f = 76°F
REF = 1.97 x 10^4

SEPARATE

P_c = 144 psia
V_f = 105 ft/sec
T_f = 294°F
REF = 7.72 x 10^4
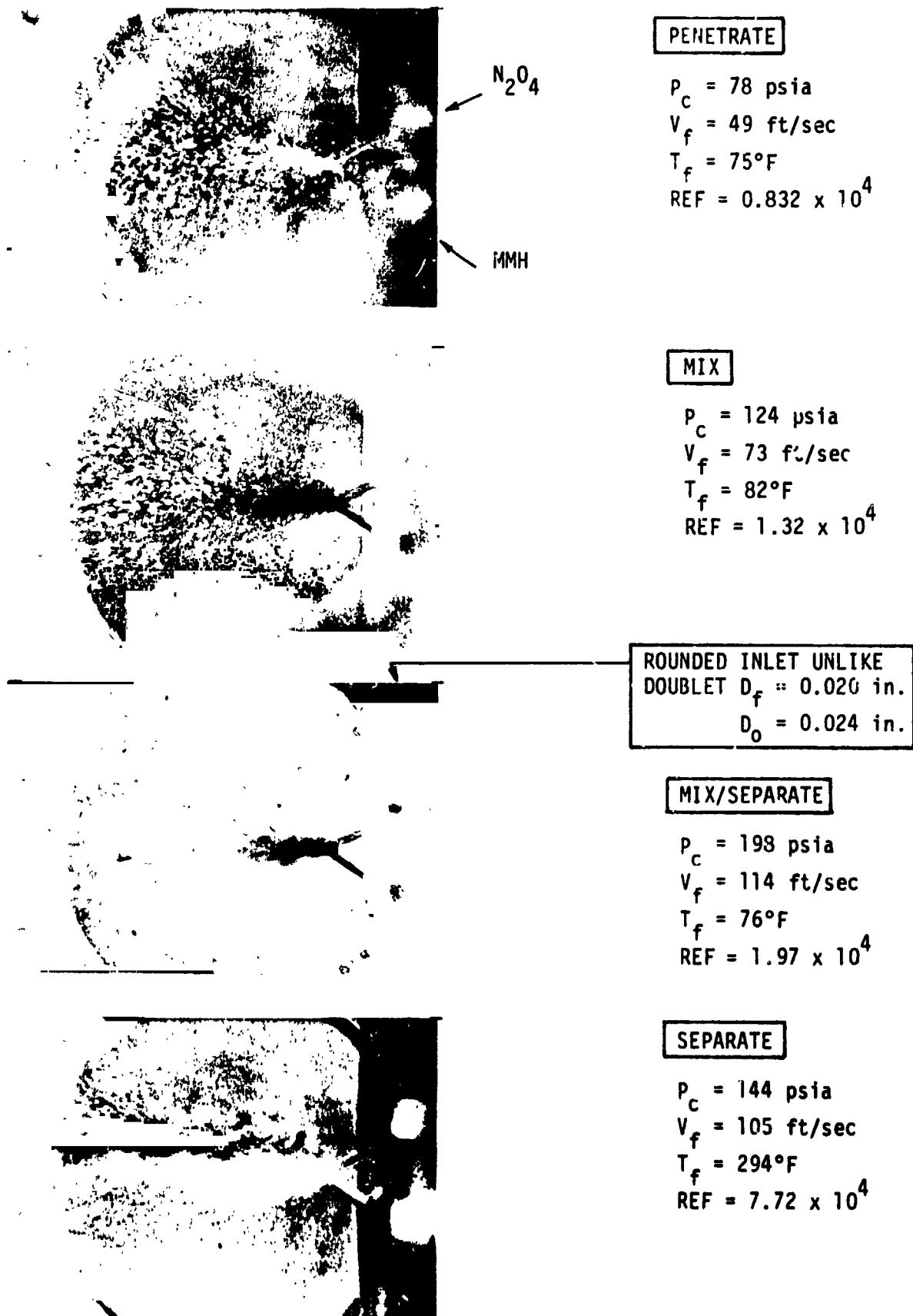
Figure 13. Reactive Stream Impingement Inhibits Intra-Element Mixing

IV, Reactive Stre..n Impingement Phenomena (cont.)

The phenomena of RSS is associated with a vaporization controlled
reaction that is controlled by the chamber pressure, fuel injection velocity,
interfacial surface area, and fuel temperature. The degree of RSS increases
as these parameters are increased. RSS has been characterized for a wide
range of amine fuels and a wide range of injectors as listed in Table II.

The RSS characteristics of all of the coherent stream elements (i.e.,
rounded inlet unlike doublet, triplet, sharp-edged unlike doublet, and Space
Shuttle/RCS unlike doublet) were found to be similar and are correlated with
the same correlation equation. The similarity in behavior for the triplet
and sharp-edged unlike doublet is shown in Figures 14 and 15. The behavior
of the Space Shuttle/RCS unlike doublet is illustrated in Figure 16 which
shows the element behavior over its whole Pc-MR operating range. The
impingement mode and operating condition is indicated next to each photo.

The off-mixture ratio momentum effects on spray mixing are seen to
be as strong as the RSS effects with the SS/RCS unlike doublet. It is
clearly undesirable to operate at extreme off-MR conditions with unlike
doublet elements due to the strong effect on spray distributions. The
triplet or pentad coherent elements or atomized spray elements which are
less sensitive to momentum effects would be better choices for injectors
that must cover wide mixture ratio ranges.

The RSS characteristics of the XDT, the splashplate, and the Space
Shuttle/OMS TLOL self-atomizing elements were found to differ from the
coherent stream elements in that RSS occurs at lower chamber pressures than
for the coherent stream elements. The RSS characteristics of the XDT
and the splashplate elements are illustrated in Figures 17 and 18. Increasing
chamber pressure and fuel Reynolds Number (REF) promotes RSS. The chamber
pressure is a much stronger effect than the fuel velocity (REF) as evidenced

TABLE II

SUMMARY OF INJECTOR ELEMENTS AND TEST CONDITIONS

INJECTOR ELEMENT	FUEL	P_c (psia)	V_f (ft/sec)	V_o (ft/sec)	T_f (°F)	T_o (°F)	MR.
Rounded Inlet Unlike Doublet, $D_f = 0.020$	MMH	80-1000	35-160	30-111	55-300	55-150	1.60-1.70
	A-50	90-1000	50-162	40-114	60-85	55-80	1.60-1.70
	N_2H_4	60-300	40-165	34-130	65-160	68-76	1.60-1.70
Small F-O-F Triplet $D_f = 0.020$	MMH	80-210	40-100	30-70	70-300	60-145	1.60-1.70
Large F-O-F Triplet $D_f = 0.029$	MMH	80-195	30-78	32-65	75-300	68-150	1.60-1.70
Small Sharp Edged Unlike Doublet - $D_f = 0.020$	MMH	68-396	35-216	26-150	68-245	68-104	1.60-1.70
	N_2H_4	75-392	40-160	34-125	73-173	66-82	1.60-1.70
Large Sharp Edged Unlike Doublet, $D_f = 0.030$	MMH	80-310	34-174	30-110	68-265	66-136	1.60-1.70
	N_2H_4	34-410	30-175	30-150	66-80	64-85	1.60-1.70
Space Shuttle/RCS Unlike Doublet, $D_f = 0.023$	MMH	83-247	28-119	25-142	53-137	47-123	1.36-3.15
Space Shuttle/RCS Unlike Doublet, Offset Impingement, $D_f = 0.023$	MMH	114-193	61-106	36-105	75-87	68-80	1.45-3.06
Space Shuttle/OMS TLOL Platelet Injector $D_f = 0.023$	MMH	43-195	29-127	26-112	65-231	62-83	1.44-1.81
	N_2H_4	104-397	38-120	40-112	71-155	70-73	1.43-1.96
XDT Platelet, $D_f = 0.021$	MMH	81-194	42-100	32-80	68-291	62-162	1.60-1.70
Splashplate Platelet, $D_f = 0.021$	MMH	81-192	40-104	32-80	71-288	71-154	1.60-1.70

30

SMALL F-O-F TRIPLET

$D_f = 0.020$

$D_0 = 0.034$

MMH

N₂O₄

MMH

MIX

$P_c = 101$ psia

$V_f = 50$ ft/sec

$T_f = 80°F$

$REF = 0.9 \times 10^4$

OF POOR QUALITY

SEP

P_c, PSIA

N₂O₄/MMH CORRELATION

MIX

REF

SEPARATE

$P_c = 156$ psia

$V_f = 91$ ft/sec

$T_f = 296°F$

$REF = 6.8 \times 10^4$
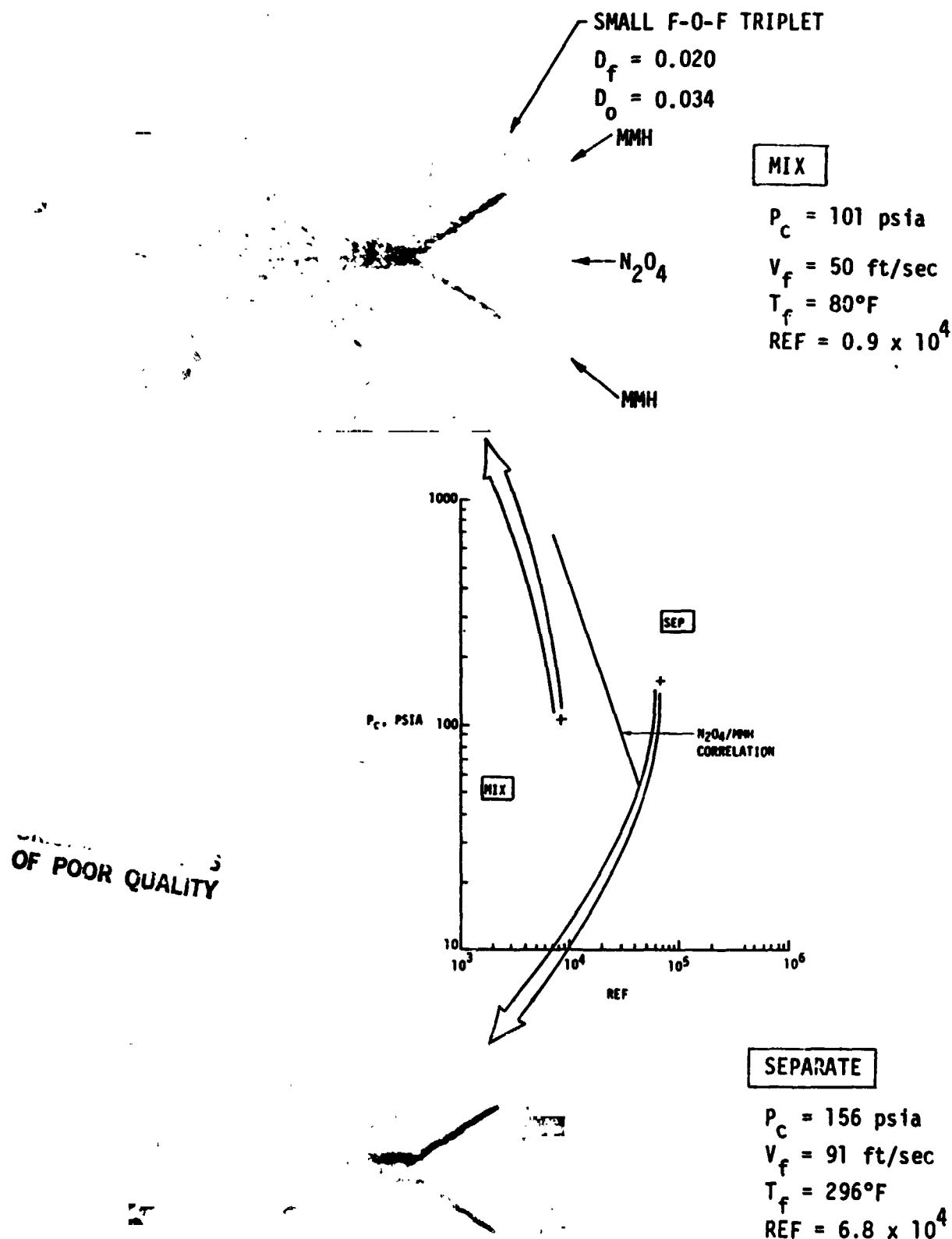
Figure 14.   Reactive Stream Impingement with the F-O-F Triplet Element

31

SMALL SHARP EDGED UNLIKE DOUBLET

D_f = 0.020 in.

D_o = 0.024 in.

N_2O_4

MMH

MIX

P_c = 103 psia

V_f = 119 ft/sec

T_f = 70°F

REF = 1.95 x 10^4

SEP

P_c, PSIA   100

N_2O_4/MMH
CORRELATION

MIX

10^3 10^4 10^5 10^6

REF

SEPARATE

P_c = 191 psia

V_f = 117 ft/sec

T_f = 73°F

REF = 1.97 x 10^4
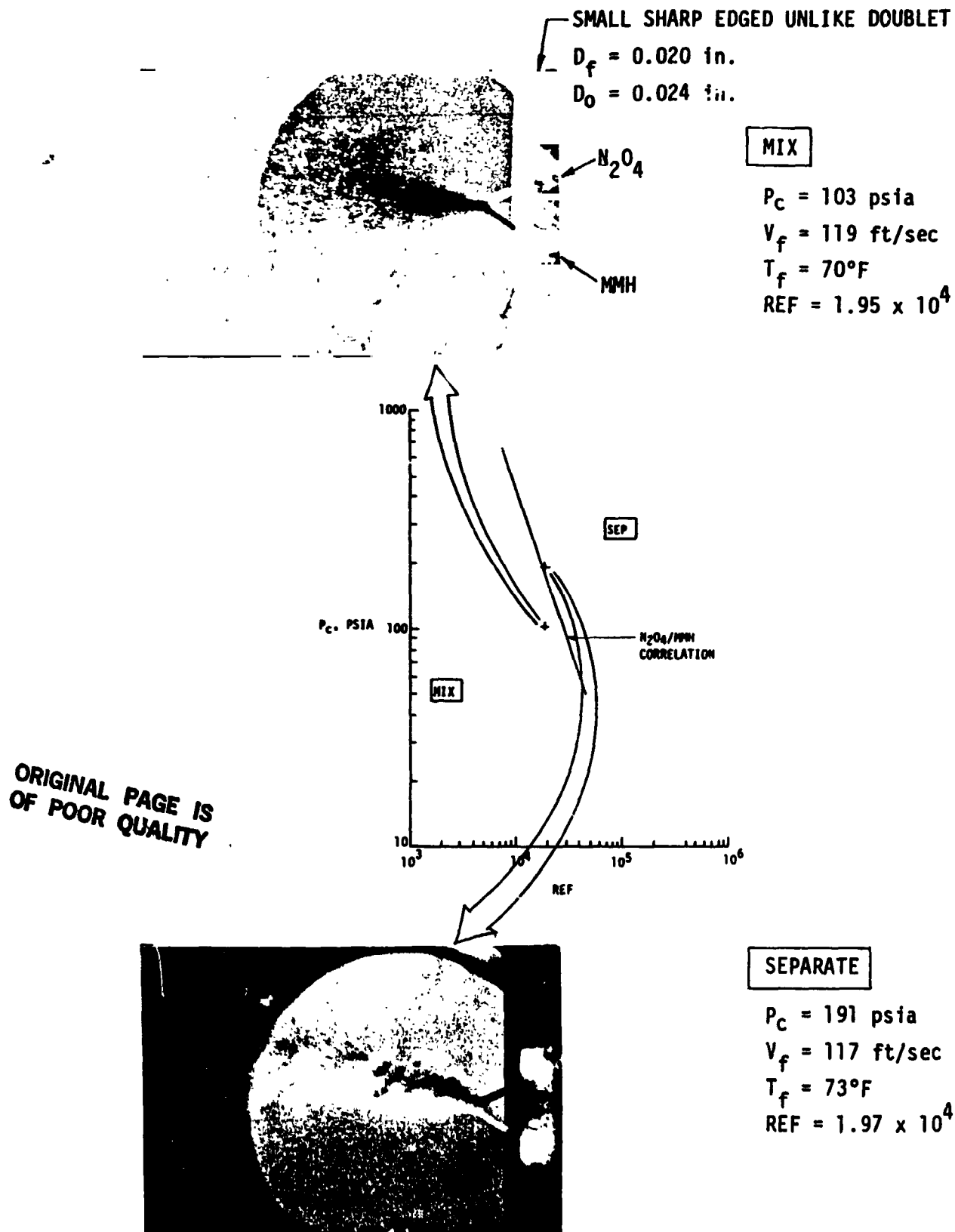
Figure 15.   Reactive Stream Impingement with the Sharp Edged Unlike Doublet

32
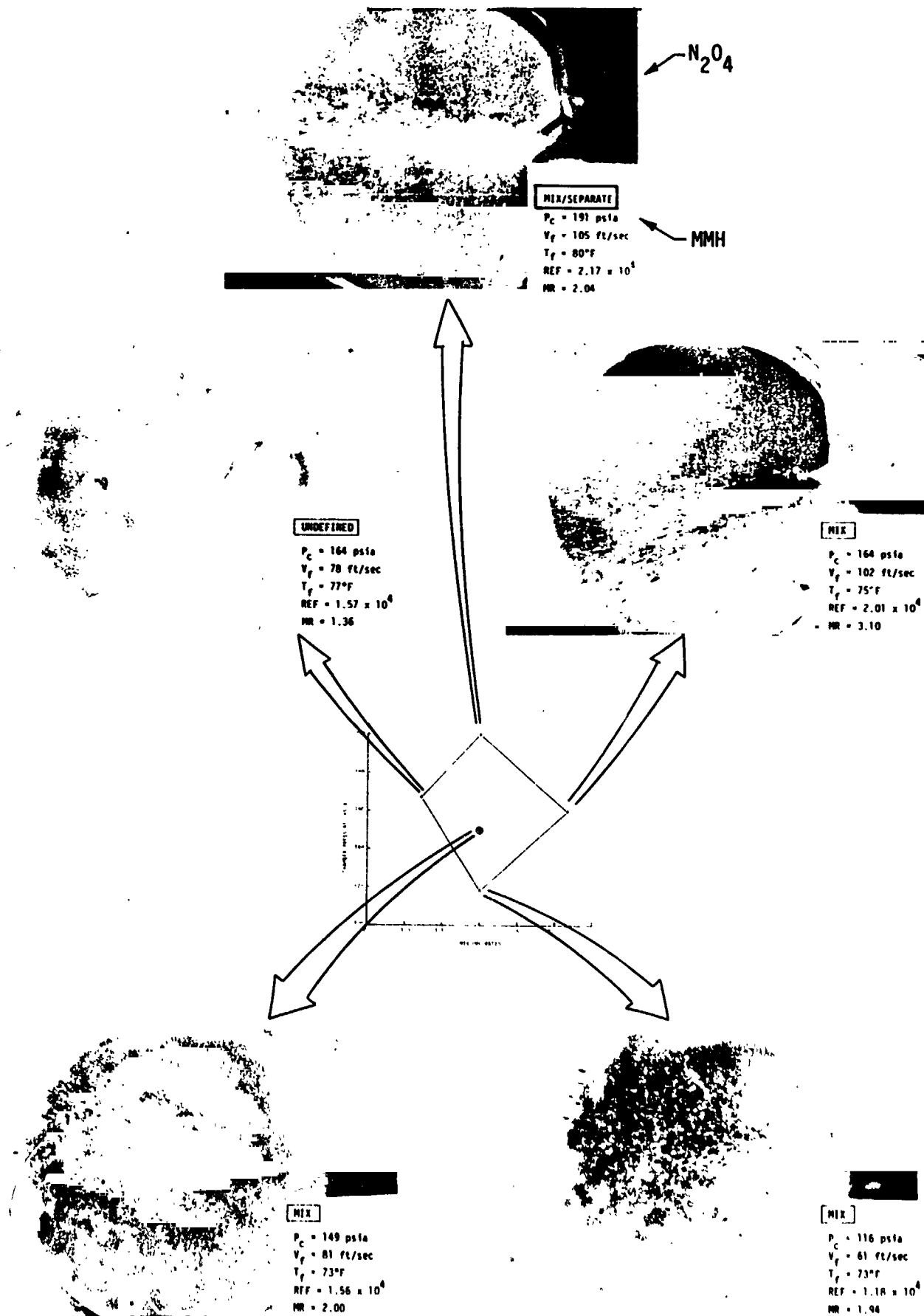
Figure 16.   Reactive Stream Impingement with the Space Shuttle/RCS Unlike
Doublet
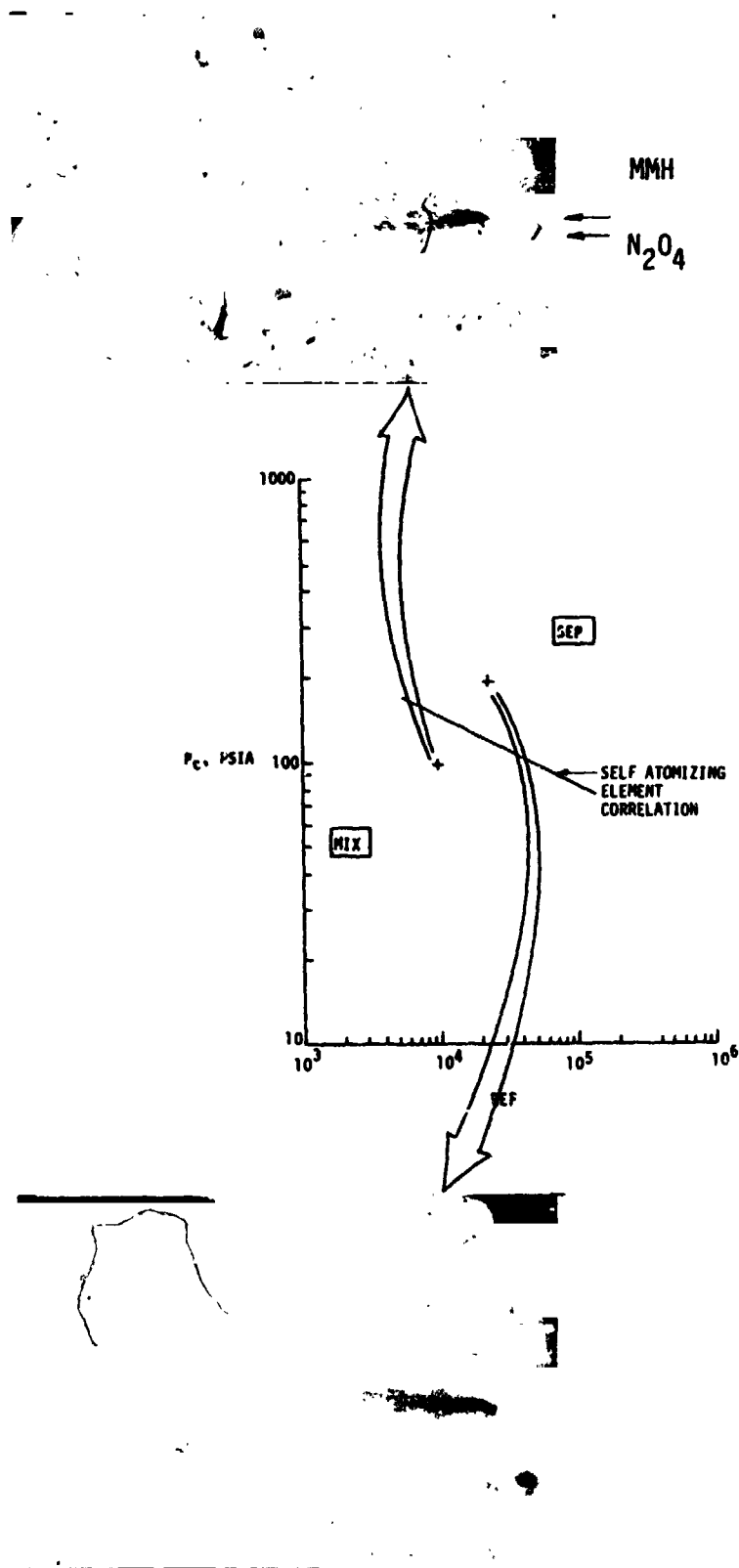
Figure 17. Reactive Stream Impingement with the XDT Platelet Element

34

SPLASH PLATE PLATELET ELEMENT

D_f = 0.021 in.

MMH

MIX

P_c = 102 psia

V_f = 48 ft/sec

T_f = 72°F

REF = 0.844 x 10^4

N_2O_4

SEP

SELF ATOMIZING
ELEMENT
CORRELATION

P_c = 1272 $(REF)^{-0.24}$

MIX

P_c, PSIA

1000

100

10

10^3 10^4 10^5 10^6

REF

SEPARATE

P_c = 186 psia

V_f = 104 ft/sec

T_f = 79°F

REF = 1.94 x 10^4
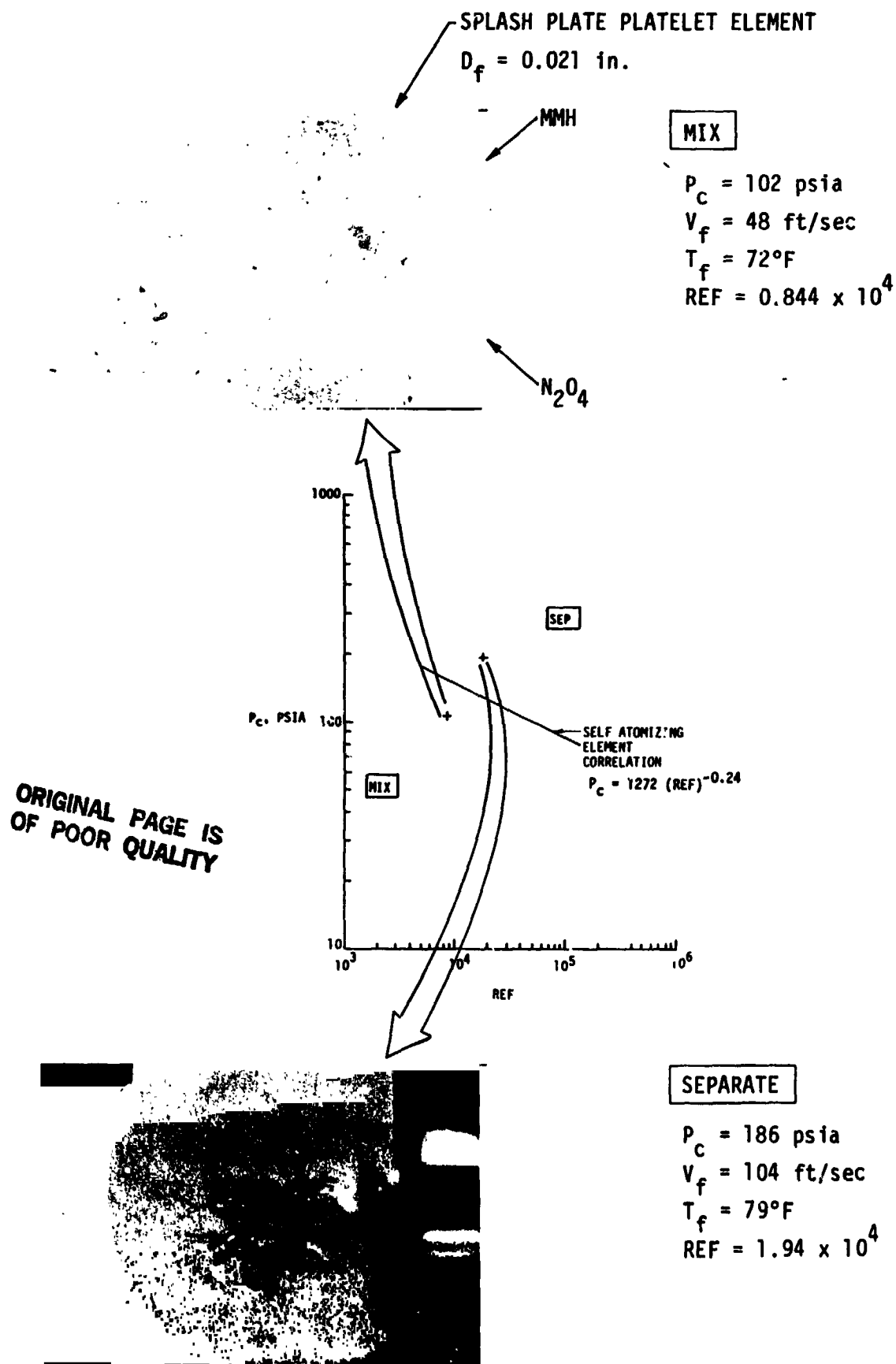
Figure 18.   Reactive Stream Impingement with the Splashplate Element

IV, Reactive Stream Impingement Phenomena (cont.)

by the small slope of the correlation line. RSS sets in at such low chamber pressure levels (∿100 psia) that these elements generally always operate in the separated mode.

The Space Shuttle/OMS TLOL platelet element is an example of an element that operates in a separated mode over its entire operating range as illustrated in Figure 19. The operating conditions are indicated next to each photo. It is evident that this element is insensitive to engine operating mode. Although, it is always separated, the desired engine performance is attained by providing element overlap to take advantage of inter-element mixing. Excellent performance, compatibility and stability are provided by this element since the injector spray mass and mixture ratio distribution remain nearly constant over its whole operating range.

MMH

N_2O_4

SEPARATE
P_c = 140 psia
V_f = 73 ft/sec
T_f = 220°F
REF = 4.81 x 10^4
MR = 1.61

SEPARATE
P_c = 132 psia
V_f = 74 ft/sec
T_f = 226°F
REF = 5.07 x 10^4
MR = 1.47

SEPARATE
P_c = 131 psia
V_f = 64 ft/sec
T_f = 218°F
REF = 4.16 x 10^4
MR = 1.81

SEPARATE
P_c = 110 psia
V_f = 65 ft/sec
T_f = 226°F
REF = 4.42 x 10^4
MR = 1.46

SEPARATE
P_c = 113 psia
V_f = 56 ft/sec
T_f = 214°F
REF = 3.53 x 10^4
MR = 1.80

SEPARATE
P_c = 103 psia
V_f = 54 ft/sec
T_f = 217°F
REF = 3.52 x 10^4
MR = 1.65
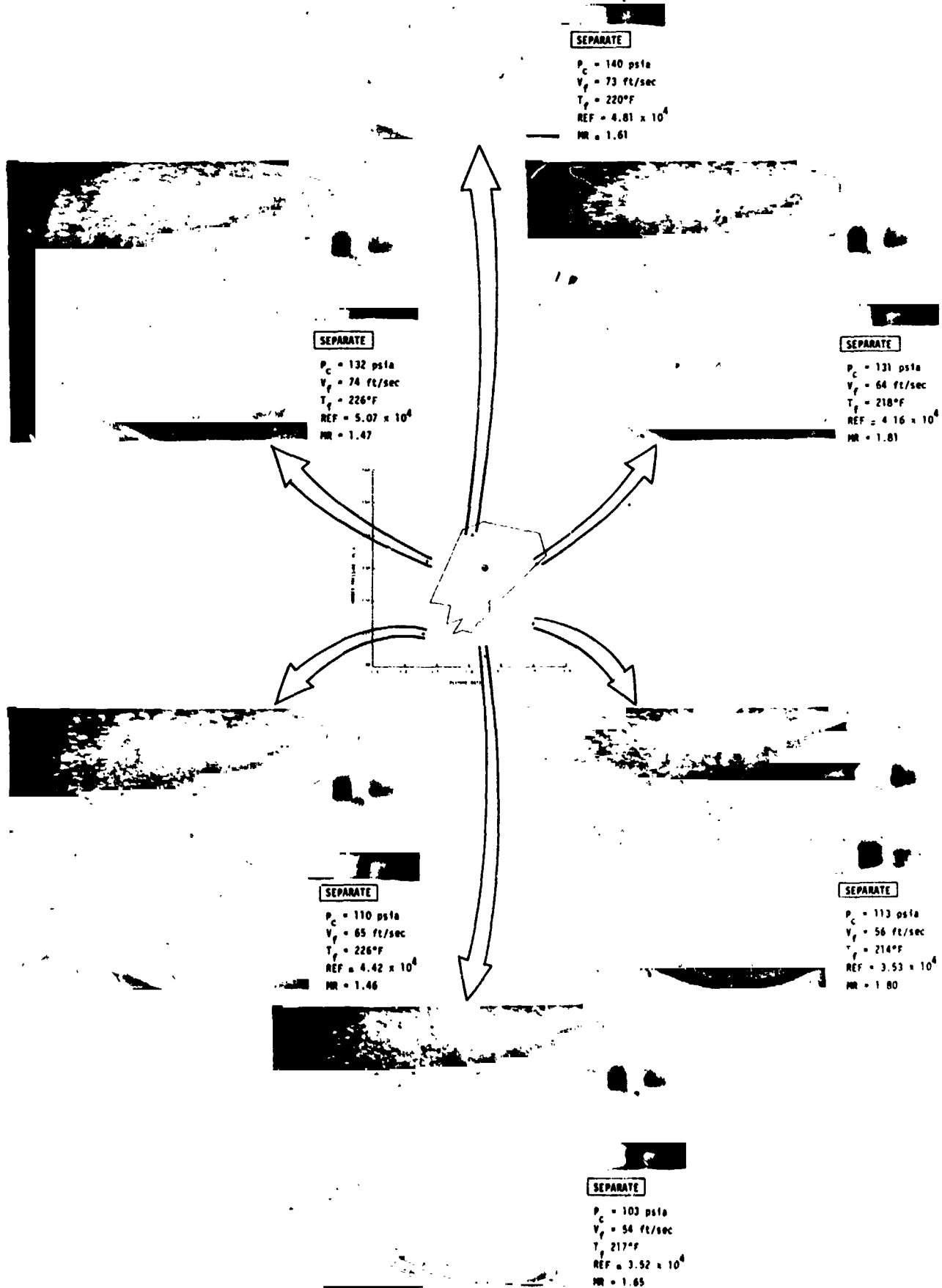
Figure 19. Reactive Stream Impingement with the Space Shuttle/OMS
TLOL Platelet Element

27

Appendix A

V.   REACTIVE STREAM IMPINGEMENT DATA CORRELATIONS

RSS has been found to correlate best with the chamber pressure and
the fuel orifice Reynolds Number. Figure 20 shows the correlation for coherent
stream injectors while Figure 21 shows the atomized spray impingement injector
correlations. The coherent stream injectors are correlated with the equation;

$$Pc = 4.4 \times 10^8 (REF)^{-1.5} \qquad \text{Equation (3)}$$

where:

$$REF = \text{Fuel Orifice Reynolds Number.}$$

Mixing occurs at chamber pressures less than that specified by Equation (3)
and separation occurs at greater chamber pressures. Regimes of RSS with
the atomized spray impingement platelet types of injectors are correlated by:

$$Pc = 1272 (REF)^{-0.24} \quad \text{(XDT and splash plate)} \qquad \text{Equation (4)}$$
$$Pc = 839 (REF)^{-0.24} \text{ (TLOL)}. \qquad \text{Equation (5)}$$

Again mixing occurs at chamber pressures below this value and separation
occurs at pressures greater than this.
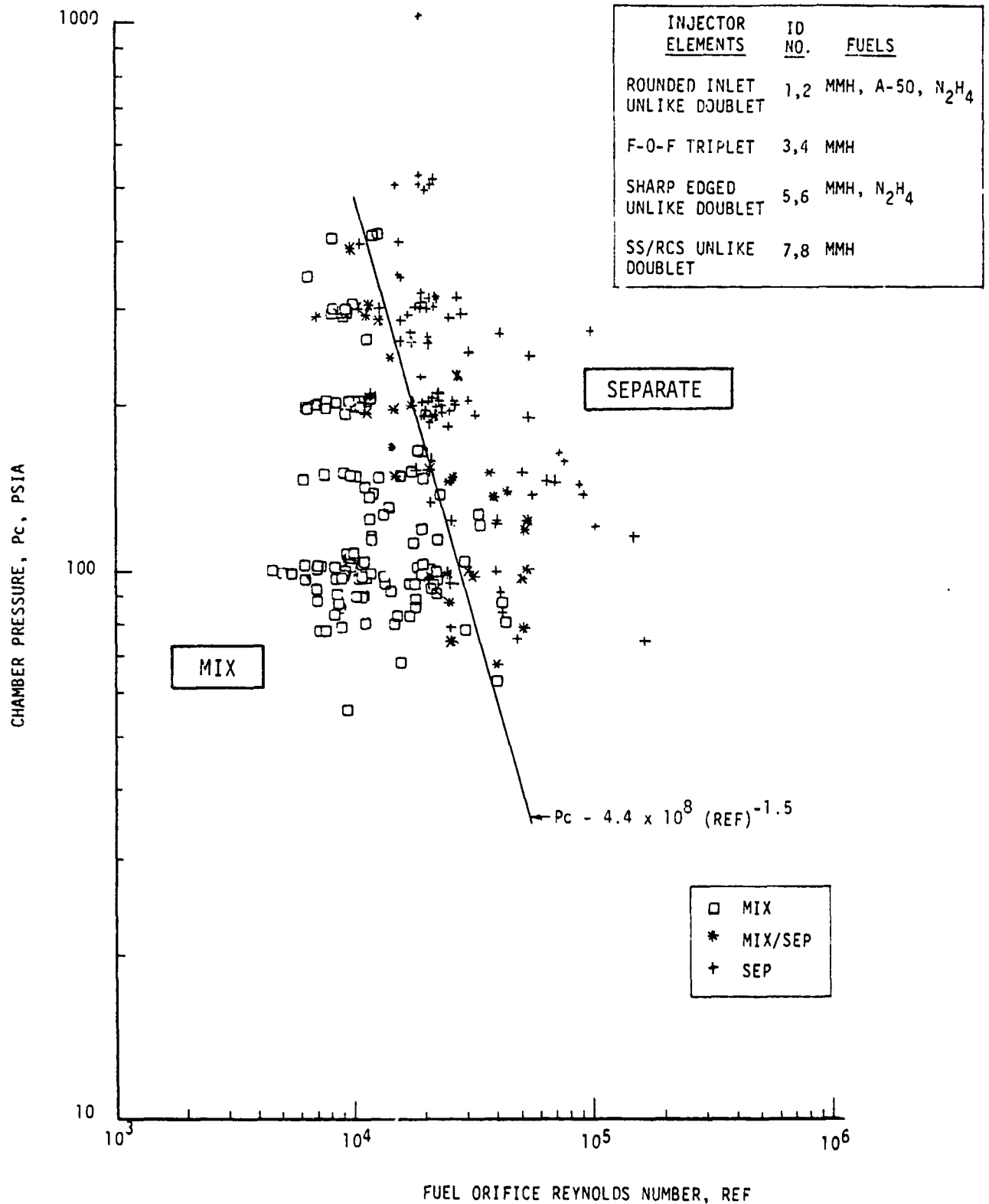
Figure 20. RSS Correlation for Coherent Stream Impingement Injector Elements

Figure 21 Vaporization Model Correlates RSS for Self-
Atomizing Injector Elements

Appendix A

VI. REACTIVE STREAM DESIGN CRITERIA

The intent of the design criteria set forth herein is to aid the
injector designer in coping with the adverse effects of RSS on engine
performance, stability, and compatibility. Since these effects manifest
themselves through modifications to the intra- and inter-element mixing,
only those factors influencing the mixing processes are dealt with. It
is presumed that other factors influencing performance, stability and com-
patibility have been considered. These other factors include but are
not limited to; identification of element size and quantity to provide the
required vaporization efficiency; pattern orientation requirements for inter-
element mixing and compatibility; chug stability pressure drop requirements.

A prerequisite for designing high performance elements is to provide
for hydraulically stable streams or sprays. Therefore, non-reactive im-
pingement criteria are included.

A. NON-REACTIVE IMPINGEMENT ELEMENT DESIGN CRITERIA

Criteria 1   Orifice discharge coefficients should be predictable
                    and should not undergo hydraulic flip.

Solution
° Design sharp edged orifices with L/D < 1 to ensure
  detached flow.

° Design sharp edged orifices with L/D > 4 to
  ensure attached flow.

° Contour orifice inlet

Criteria 2   Stream directional control should be predictable.

Appendix A

Solution

° Design orifice L/D > 4 with contoured inlet.

° Design manifold cross velocity for less than 1/4
orifice velocity.

Criteria 3   Stream impingement should be accurately aligned.

Solution

° Electrical Discharge Machine (EDM) orifices.

Criteria 4   Unlike orifice diameter or spray mismatch should be
minimized.

Solution

° Select element types that minimize unlike orifice
diameters (see Table I).

° Select non-circular orifices.

° Design for equal spray fan width.

Criteria 5   Momentum ratios should be selected for optimum mixing.

Solution

° Use mixing criteria listed in Table I for the
particular element of interest.

Appendix A

VI, Reactive Stream Design Criteria (cont.)

B.   REACTIVE IMPINGEMENT ELEMENT DESIGN CRITERIA

Criteria 1   RSS should be avoided to maximize performance.

Solution

° Select element size and velocity that will permit
  operation within the mix regimes defined by
  Equations (3) and (4) and (5).

Criteria 2   ° Transitions from mixed to separated conditions within
                   the engine operating envelope should be avoided.

Solution

° Select elements that will remain within either the
  mixed or separated regimes defined by Equations (3)
  and (4) and (5).

Criteria 3   ° Changes in resultant axial momentum angle within the
                   engine operating envelope should be avoided.

Solution

° Select elements that are insensitive to momentum
  imbalance (triplets, pentads, like-on-like).

Criteria 4   ° Inter-element mixing should be maximized.

Solution

° Orient elements within the pattern to provide spray
  overlap taking into account the effect of RSS on
  intra-element mixing.

Appendix A

REFERENCES

1. Rupe, J.H., "A Correlation Between the Dynamic Properties of a Pair of Impinging Streams and the Uniformity of Mixture-Ratio Distribution in the Resulting Spray", JPL Progress Rept. No. 20-209, 1956.

2. Rupe, J.H., "An Experimental Correlation of the Nonreactive Properties of Injection Schemes and Combustion Effects in a Liquid Propellant Rocket Engine, Part I. The Application of Nonreactive Spray Properties to Rocket Motor Injector Design", JPL Tech. Rept. 32-255, July 1965.

3. Elverum, G.W. and Morey, T.F., "Criteria for Optimum Mixture Ratio Distributions Using Several Types of Impinging Stream Injector Elements", JPL Memorandum No. 30-5, February 1959.

4. McHale, R.M. and Nurick, W.H., "Noncircular Orifice Holes and Advanced Fabrication Techniques for Liquid Rocket Injectors", Rocketdyne Report R-9271, Contract No. NAS 9-9528, May 1974.

5. Ito, J.I., "A General Model Describing Hydraulic Flip in Sharp Edge Orifices", 7th JANNAF Combustion Meeting, Expanded Abstracts and Slides - Volume I, CPIA Publ. #204, Vol. 1; Feb. 1971.

TABLE B-I

SUMMARY OF INJECTOR ELEMENTS AND TEST CONDITIONS

INJECTOR ELEMENT	FUEL	P_c (psia)	V_f (ft/sec)	V_o (ft/sec)	T_f (°F)	T_o (°F)	NO. OF TESTS	MR
Rounded Inlet Unlike Doublet, $D_f = 0.020$	MMH	80-1000	35-160	30-111	55-300	55-150	96	1.60-1.70
	A-50	90-1000	50-162	40-114	60-85	55-80	32	1.60-1.70
	N_2H_4	60-300	40-165	34-130	65-160	68-76	21	1.60-1.70
Small F-O-F Triplet, $D_f = 0.020$	MMH	80-210	40-100	30-70	70-300	60-145	12	1.60-1.70
Large F-O-F Triplet, $D_f = 0.029$	MMH	80-195	30-78	32-65	75-300	68-150	11	1.60-1.70
Small Sharp Edged Unlike Doublet - $D_f = 0.020$	MMH	68-396	35-216	26-150	68-245	68-104	24	1.60-1.70
	N_2H_4	75-392	40-160	34-125	73-173	66-82	17	1.60-1.70
Large Sharp Edged Unlike Doublet, $D_f = 0.030$	MMH	80-310	34-174	30-110	68-265	66-136	15	1.60-1.70
	N_2H_4	84-410	30-175	30-150	66-80	64-85	16	1.60-1.70
Space Shuttle/RCS Unlike Doublet, $D_f = 0.023$	MMH	83-247	28-119	25-142	50-137	47-123	43	1.36-3.15
Space Shuttle/RCS Unlike Doublet, Offset Impingement, $D_f = 0.023$	MMH	114-193	61-106	36-105	75-87	68-80	7	1.45-3.06
Space Shuttle/OMS TLOL Platelet Injector $D_f = 0.028$	MMH	43-195	29-127	26-112	65-231	62-83	19	1.44-1.81
	N_2H_4	104-397	38-120	40-112	71-155	70-78	12	1.43-1.96
XDT Platelet, $D_f = 0.021$	MMH	81-194	42-100	32-80	68-291	62-162	16	1.60-1.70
Splashplate Platelet, $D_f = 0.021$	MMH	81-192	40-104	32-80	71-288	71-154	15	1.60-1.70
							356	

Appendix B

TABLE B-II

SUMMARY OF INJECTOR ELEMENT TEST RESULTS

List of Symbols
Description of Headings for Table B-II

D_f, D_o	Fuel and oxidizer orifice diameter, in.
DELTI	Impingement point temperature rise, °F
Imp. Angle	Propellant Stream Impingement angle, °
L/D	Orifice length to diameter ratio
MF/MO	Fuel to oxidizer momentum ratio
MR	Oxidizer to fuel mixture ratio
MRVP	Vapor phase mixture ratio
Pc	Chamber pressure, psia
PPF, PPO	Fuel and oxidizer partial pressures, psia
REACT	Reactivity, Re_f x XP
REF, REO	Fuel and oxidizer orifice Reynolds Number based on dia
RELF, RELO	Fuel and oxidizer orifice Reynolds No., based on length
RESID	Propellant stream contact time, sec.
TF	Fuel temperature, °F
TO	Oxidizer temperature, °F
VAVG	Average of fuel and oxidizer injection velocity, ft/sec
VF, VO	Fuel and oxidizer injection velocity, ft/sec
WEF, WEO	Fuel and oxidizer Weber No.
XF, XO	Fuel and oxidizer mole fraction
XP	Product of fuel and oxidizer mole fraction ** 1/2

TABLE B-II (cont.)

HYPERGOLIC STREAM IMPINGMENT DATA COMPILATION

INVESTIGATOR LAWVER

TEST SERIES OC-27-XXX

FUEL TYPE	TEST NO.	INJECTOR TYPE	DO (IN)	DF (IN)	L/D	IMP ANGLE (DEG)	PC (PSIA)	VO (FT/S)	VF (FT/S)	TO (F)	TF (F)	MR	MF/MO	MODE	REACT (SEC)
MMH	101	UNLIKE-DOUBLET	.024	.020	24.	60.	308.	90.5	129.1	88.	87.	1.66	1.239	SEP	.442+03
MMH	102	UNLIKE-DOUBLET	.024	.020	24.	60.	308.	87.2	132.5	86.	87.	1.57	1.381	SEP	.454+03
MMH	103	UNLIKE-DOUBLET	.024	.020	24.	60.	309.	89.4	129.9	87.	87.	1.62	1.286	SEP	.444+03
MMH	104	UNLIKE-DOUBLET	.024	.020	24.	60.	311.	88.3	129.1	88.	87.	1.62	1.301	SEP	.438+03
MMH	105	UNLIKE-DOUBLET	.024	.020	24.	60.	507.	90.5	125.7	88.	88.	1.70	1.175	SEP	.270+03
MMH	106	UNLIKE-DOUBLET	.024	.020	24.	60.	1000.	92.0	138.5	89.	88.	1.57	1.381	SEP	.151+03
MMH	107	UNLIKE-DOUBLET	.024	.020	24.	60.	308.	89.4	124.7	86.	85.	1.70	1.176	SEP	.401+03
MMH	108	UNLIKE-DOUBLET	.024	.020	24.	60.	263.	86.6	124.0	84.	84.	1.65	1.259	SEP	.449+03
MMH	109	UNLIKE-DOUBLET	.024	.020	24.	60.	197.	94.6	136.5	84.	84.	1.64	1.260	SEP	.656+03
MMH	110	UNLIKE-DOUBLET	.024	.020	24.	60.	158.	47.3	129.5	83.	83.	1.60	1.312	SEP	.752+03
MMH	111	UNLIKE-DOUBLET	.024	.020	24.	63.	130.	92.3	135.5	84.	84.	1.59	1.308	MIX	.126+04
MMH	112	UNLIKE-DOUBLET	.024	.020	24.	60.	89.	51.1	73.0	76.	70.	1.59	1.308	MIX	.759+03
A-50	113	UNLIKE-DOUBLET	.024	.020	24.	60.	101.	91.5	128.0	88.	87.	1.63	1.232	MIX	.169+04
A-50	114	UNLIKE-DOUBLET	.024	.020	24.	60.	162.	85.3	117.9	82.	82.	1.64	1.209	MIX	.806+03
A-50	115	UNLIKE-DOUBLET	.024	.020	24.	60.	203.	91.0	125.9	81.	78.	1.65	1.203	SEP	.624+03
A-50	116	UNLIKE-DOUBLET	.024	.020	24.	60.	289.	83.4	114.4	80.	77.	1.67	1.181	SEP	.414+03
A-50	117	UNLIKE-DOUBLET	.024	.020	24.	60.	301.	61.4	85.7	78.	76.	1.60	1.217	SEP	.426+03
A-50	118	UNLIKE-DOUBLET	.024	.020	24.	60.	310.	80.7	123.6	78.	81.	1.60	1.277	SEP	.424+03
A-50	119	UNLIKE-DOUBLET	.024	.020	24.	60.	510.	85.7	120.4	82.	82.	1.64	1.249	SEP	.201+03
A-50	120	UNLIKE-DOUBLET	.024	.020	24.	60.	1003.	87.8	122.8	81.	81.	1.63	1.227	SEP	.132+03
A-50	121	UNLIKE-DOUBLET	.024	.020	24.	60.	160.	84.4	125.2	81.	80.	1.62	1.247	MIX	.815+03
A-50	122	UNLIKE-DOUBLET	.024	.020	20.	60.	130.	72.8	100.6	81.	80.	1.65	1.200	SEP	.310+03
A-50	123	UNLIKE-DOUBLET	.024	.020	24.	60.	334.	75.3	104.6	77.	77.	1.65	1.293	SEP	.295+03
MMH	124	UNLIKE-DOUBLET	.024	.020	24.	60.	955.	89.6	101.6	82.	82.	1.61	1.293	SEP	.942+02
MMH	125	UNLIKE-DOUBLET	.024	.020	24.	60.	495.	84.4	130.3	83.	81.	1.60	1.315	SEP	.231+03
MMH	126	UNLIKE-DOUBLET	.024	.020	24.	60.	296.	86.4	132.1	83.	82.	1.59	1.350	SEP	.394+03
MMH	127	UNLIKE-DOUBLET	.024	.020	24.	60.	245.	53.7	60.5	84.	81.	1.58	1.372	M/S	.253+03
MMH	128	UNLIKE-DOUBLET	.024	.020	24.	60.	256.	89.8	120.2	85.	83.	1.54	1.347	SEP	.463+03
MMH	129	UNLIKE-DOUBLET	.024	.020	24.	60.	191.	91.0	135.5	85.	83.	1.60	1.351	SFP	.607+03
MMH	130	UNLIKE-DOUBLET	.024	.020	24.	60.	152.	85.9	129.5	84.	82.	1.56	1.384	M/S	.784+03
MMH	131	UNLIKE-DOUBLET	.024	.020	24.	60.	95.	84.4	133.0	85.	83.	1.57	1.366	MIX	.135+04
MMH	132	UNLIKE-DOUBLET	.024	.020	24.	60.	114.	91.4	136.4	86.	83.	1.58	1.357	MIX	.114+04
MMH	133	UNLIKE-DOUBLET	.024	.020	24.	60.	411.	125.8	179.6	83.	83.	1.66	1.238	UNDEF	.400+03
MMH	134	UNLIKE-DOUBLET	.024	.020	24.	60.	97.	92.8	136.1	77.	197.	1.74	1.216	M/S	.103+05
MMH	135	UNLIKE-DOUBLET	.024	.020	24.	60.	119.	93.8	139.2	78.	199.	1.72	1.247	M/S	.894+04
MMH	136	UNLIKE-DOUBLET	.024	.020	24.	60.	150.	92.4	136.5	77.	199.	1.74	1.227	SEP	.687+04
MMH	137	UNLIKE-DOUBLET	.024	.020	24.	60.	188.	97.7	143.8	76.	199.	1.74	1.218	SEP	.570+04
MMH	138	UNLIKE-DOUBLET	.024	.020	24.	60.	243.	95.3	148.9	79.	195.	1.60	1.434	SEP	.442+04
MMH	139	UNLIKE-DOUBLET	.024	.020	24.	60.	103.	35.3	58.9	61.	59.	1.45	1.615	UNDEF	.226+03
MMH	140	UNLIKE-DOUBLET	.024	.020	24.	60.	81.	97.4	143.0	64.	62.	1.61	1.306	UNDEF	.760+03

TABLE B-II (cont.)

HYPERGOLIC STREAM IMPINGMENT DATA COMPILATION

INVESTIGATOR LANVER

FUEL TYPE	TEST NO.	MODE	PC (PSIA)	VAVG	WEF	WEO	REF	REO	DELT1 (DEG F)	RELF	RELO	PPF (PSIA)	PPO (PSIA)	HRVP	XF	XO	XP	RESID
MMH	101	SFP	308.	105.	43.7	36.0	.245+05	.051+05	0.	.59+06	.16+07	1.3	23.2	34.8	.0020990	.0020990	.85-08	.44+03
MMH	102	SFP	308.	105.	40.0	34.0	.252+05	.632+05	0.	.63+06	.15+07	1.3	23.2	34.6	.0021107.	.0021107.	.86-08	.45+03
MMH	103	SFP	309.	105.	44.7	35.2	.681+05	.681+05	0.	.59+06	.15+07	1.3	23.2	34.8	.0021122.	.0021122.	.85-08	.44+03
MMH	104	SFP	311.	104.	44.1	34.6	.245+05	.855+05	0.	.59+06	.15+07	1.3	23.7	34.8	.0021473.	.0021473.	.85-08	.44+03
MMH	105	SFP	507.	110.	68.3	59.0	.265+05	.655+05	0.	.58+06	.16+07	1.4	23.7	34.8	.0022487.	.0022487.	.87-08	.27+03
MMH	106	SFP	1000.	163.5	163.5	121.6	.265+05	.666+05	0.	.64+06	.16+07	1.4	22.1	34.8	.0021094.	.0021094.	.87-08	.15+03
MMH	107	SFP	508.	103.	34.2	34.9	.231+05	.639+05	0.	.50+06	.15+07	1.3	21.1	34.0	.0021319.	.0021319.	.82-08	.40+03
MMH	108	SFP	263.	101.	31.1	27.5	.253+05	.697+05	0.	.55+06	.15+07	1.2	21.1	34.0	.0018579.	.0018579.	.76-08	.45+03
MMH	109	SFP	197.	111.	22.5	24.7	.238+05	.665+05	0.	.61+06	.15+07	1.2	20.0	34.0	.0018768.	.0018768.	.76-08	.66+03
MMH	110	SFP	158.	104.	15.5	17.0	.249+05	.615+05	0.	.57+06	.16+07	1.1	21.1	34.8	.0018653.	.0018653.	.77-08	.13+03
MMH	111	MTX	100.	100.	4.7	11.9	.117+05	.647+05	0.	.40+06	.82+06	2.1	17.9	34.8	.0203051.	.0203051.	.57-08	.76+03
A-50	112	MTX	101.	105.	16.8	3.1	.211+05	.342+05	0.	.27+06	.16+07	2.0	23.0	17.9	.0217658.	.0217658.	.49-08	.17+03
A-50	113	MTX	102.	93.	21.8	12.1	.186+05	.591+05	0.	.51+06	.14+07	2.2	20.5	17.9	.0233446.	.0233446.	.61-08	.81+03
A-50	114	MTX	203.	104.	30.0	10.3	.193+05	.526+05	0.	.45+06	.15+07	2.2	19.0	19.2	.0233446.	.0233446.	.62-08	.82+03
A-50	115	SFP	269.	95.	33.8	23.1	.174+05	.571+05	0.	.44+06	.14+07	2.1	19.0	18.7	.0149765.	.0149765.	.61-08	.41+03
A-50	116	SFP	301.	71.	21.2	25.6	.129+05	.416+05	0.	.42+06	.14+07	2.1	18.0	18.7	.0149753.	.0149753.	.61-08	.27+03
A-50	117	SFP	510.	101.	45.7	32.0	.104+05	.597+05	0.	.31+06	.14+07	2.4	19.0	18.7	.0121621.	.0121621.	.59-08	.43+03
A-50	118	SFP	510.	99.	71.2	51.4	.106+05	.594+05	0.	.47+06	.14+07	2.4	20.0	17.9	.0023340.	.0023340.	.60-08	.26+03
A-50	120	SFP	1001.	103.	145.2	107.4	.195+05	.604+05	0.	.46+06	.15+07	2.4	20.5	18.4	.0022584.	.0022584.	.13-08	.13+03
A-50	121	MTX	100.	103.	24.2	17.0	.195+05	.612+05	0.	.47+06	.15+07	2.3	19.5	18.5	.0018753.	.0018753.	.60-08	.82+03
A-50	122	SFP	334.	81.	33.0	24.6	.157+05	.501+05	0.	.38+06	.12+07	2.2	17.6	17.9	.01 9.36.	.01 9.36.	.63-08	.31+03
A-50	123	SFP	334.	86.	35.1	25.6	.159+05	.507+05	0.	.36+06	.12+07	2.2	20.5	33.9	.0021848.	.0021848.	.55-08	.29+02
MMH	124	SFP	495.	82.	63.8	61.0	.185+05	.482+05	0.	.44+06	.15+07	1.1	20.5	35.8	.0021848.	.0021848.	.77-38	.99+02
MMH	125	SFP	204.	165.	70.8	54.0	.235+05	.618+05	0.	.56+06	.15+07	1.1	21.4	36.4	.0020270.	.0020270.	.76-08	.23+01
MMH	126	P/S	64.	64.	15.5	12.5	.105+05	.618+05	0.	.54+06	.90+06	1.2	21.6	35.6	.0031716.	.0031716.	.81-08	.40+03
MMH	127	SFP	256.	101.	34.5	25.4	.232+05	.376+05	0.	.56+06	.14+07	1.2	21.6	35.4	.0018225.	.0018225.	.80-08	.25+03
MMH	128	P/S	191.	102.	29.7	26.5	.249+05	.594+05	0.	.60+06	.16+07	1.2	21.6	36.0	.0021653.	.0021653.	.80-08	.46+03
MMH	129	SFP	157.	102.	21.5	15.8	.236+05	.647+05	0.	.57+04	.15+07	1.2	22.0	35.6	.0018765.	.0018765.	.82-08	.07+03
MMH	130	P/S	119.	100.	17.9	13.4	.244+05	.627+05	0.	.59+06	.16+07	1.2	20.5	36.0	.0121927.	.0121927.	.71-08	.78+03
MMH	131	MTX	811.	146.	112.1	90.4	.330+05	.817+05	0.	.79+06	.21+07	17.9	17.7	34.9	.0121928.	.0121928.	.42-08	.40+03
MMH	112	UNDEF	97.	109.	16.8	14.2	.558+05	.624+05	0.	.13+07	.15+07	18.7	18.1	2.4	.1018880.	.1018880.	.18-08	.10+05
MMH	115	M/S	119.	111.	24.1	14.2	.577+05	.635+05	0.	.14+07	.15+07	16.7	17.1	2.3	.1022822.	.1022822.	.19-08	.89+04
MMH	116	SFP	150.	109.	29.2	17.3	.566+05	.621+05	0.	.14+07	.15+07	17.2	17.1	2.3	.1217254.	.1217254.	.19-08	.89+04
MMH	117	SFP	243.	115.	40.7	24.0	.566+05	.653+05	0.	.14+07	.16+07	18.7	17.1	2.4	.1020457.	.1020457.	.18-08	.57+04
MMH	118	SFP	103.	115.	55.9	26.6	.601+05	.615+05	0.	.14+07	.15+07	17.2	18.6	2.0	.0715675.	.0715675.	.57-08	.44+03
MMH	119	UNDEF	101.	45.	2.9	1.6	.869+04	.220+05	0.	.21+06	.53+06	.6	12.9	41.2	.0107905.	.0107905.	.57-08	.22+03
MMH	100	UNDEF	81.	115.	13.5	9.7	.217+05	.608+05	0.	.52+06	.15+07	.6	12.9	41.2	.0114464.	.0114464.	.51-08	.76+03

TABLE B-II (cont.)

HYPERGOLIC STREAM IMPINGEMENT DATA COMPILATION

INVESTIGATOR LANVER

FUEL TYPE	TEST NO.	INJECTOR TYPE	OD (IN)	DF (IN)	L/D	IMP ANGLE (DEG)	PC (PSIA)	VO (FT/S)	VF (FT/S)	TO (F)	TF (F)	MR	MF/MO	MODE	REACT (SEC)
MMH	101	UNLIKE-DOUBLET	.024	.020	24.	60.	81.	90.8	143.2	66.	64.	1.60	1.329	UNDEF	.814+03
MMH	102	UNLIKE-DOUBLET	.024	.020	24.	60.	119.	91.4	136.7	68.	67.	1.59	1.357	MIX	.584+03
MMH	103	UNLIKE-DOUBLET	.024	.020	24.	60.	124.	32.9	54.2	67.	67.	1.42	1.690	UNDEF	.211+03
MMH	104	UNLIKE-DOUBLET	.024	.020	24.	60.	154.	35.9	55.7	67.	67.	1.53	1.453	UNDEF	.181+03
MMH	105	UNLIKE-DOUBLET	.024	.020	24.	60.	152.	88.2	128.6	68.	67.	1.62	1.283	SEP	.432+03
MMH	106	UNLIKE-DOUBLET	.024	.020	24.	60.	190.	90.3	135.6	68.	67.	1.57	1.372	SEP	.366+03
MMH	107	UNLIKE-DOUBLET	.024	.020	24.	60.	258.	84.7	124.2	68.	68.	1.61	1.302	SEP	.246+03
MMH	108	UNLIKE-DOUBLET	.024	.020	24.	60.	102.	37.0	58.8	68.	68.	1.49	1.523	MIX	.304+03
MMH	109	UNLIKE-DOUBLET	.024	.020	24.	60.	99.	89.7	135.6	69.	69.	1.60	1.141	MIX	.740+03
MMH	150	UNLIKE-DOUBLET	.024	.020	24.	60.	297.	90.1	131.9	70.	69.	1.62	1.298	SEP	.246+03
MMH	151	UNLIKE-DOUBLET	.024	.020	24.	60.	484.	95.9	137.8	70.	74.	1.63	1.261	SEP	.158+03
MMH	152	UNLIKE-DOUBLET	.024	.020	24.	60.	958.	101.8	148.3	78.	56.	1.62	1.291	SEP	.109+03
MMH	153	UNLIKE-DOUBLET	.024	.020	24.	60.	98.	29.0	50.3	55.	55.	1.37	1.616	M/P	.170+03
MMH	154	UNLIKE-DOUBLET	.024	.020	24.	60.	100.	30.4	41.9	54.	54.	1.66	1.225	M/P	.134+03
MMH	155	UNLIKE-DOUBLET	.024	.020	24.	60.	102.	49.3	51.1	53.	54.	1.70	1.174	MIX	.156+03
MMH	156	UNLIKE-DOUBLET	.024	.020	24.	60.	107.	51.5	77.1	58.	58.	1.52	1.472	MIX	.220+03
MMH	157	UNLIKE-DOUBLET	.024	.020	24.	60.	102.	28.9	79.2	57.	58.	1.61	1.318	MIX	.237+03
MMH	158	UNLIKE-DOUBLET	.024	.020	24.	60.	99.	30.3	35.6	47.	58.	1.94	.916	M/P	.128+03
MMH	159	UNLIKE-DOUBLET	.024	.020	24.	60.	101.	37.2	43.0	57.	58.	1.68	1.211	M/P	.156+03
MMH	160	UNLIKE-DOUBLET	.024	.020	24.	60.	102.	37.2	56.6	57.	58.	1.65	1.254	M/P	.201+03
MMH	161	UNLIKE-DOUBLET	.024	.020	24.	60.	102.	41.5	58.2	57.	58.	1.58	1.429	M/P	.205+03
MMH	162	UNLIKE-DOUBLET	.024	.020	24.	60.	100.	50.4	58.0	56.	58.	1.82	1.027	M/P	.199+03
MMH	163	UNLIKE-DOUBLET	.024	.020	24.	60.	98.	50.1	85.1	56.	57.	1.63	1.277	MIX	.311+03
MMH	164	UNLIKE-DOUBLET	.024	.020	24.	60.	95.	72.3	72.1	55.	57.	1.65	1.249	MIX	.248+03
MMH	165	UNLIKE-DOUBLET	.024	.020	24.	60.	99.	92.1	106.7	44.	57.	1.61	1.713	MIX	.387+03
MMH	166	UNLIKE-DOUBLET	.024	.020	24.	60.	95.	51.0	134.3	44.	55.	1.63	1.282	MIX	.242+03
MMH	167	UNLIKE-DOUBLET	.024	.020	24.	60.	99.	51.6	74.7	44.	55.	1.63	1.262	MIX	.244+03
MMH	168	UNLIKE-DOUBLET	.024	.020	24.	60.	95.	52.0	75.1	44.	44.	1.66	1.267	UNDEF	.160+03
MMH	169	UNLIKE-DOUBLET	.024	.020	24.	60.	95.	112.0	164.0	44.	44.	1.62	1.223	MIX	.172+03
MMH	170	UNLIKE-DOUBLET	.024	.020	24.	60.	95.	111.0	161.0	44.	44.	1.63	1.261	MIX	.342+03
MMH	171	UNLIKE-DOUBLET	.024	.020	24.	60.	196.	44.8	57.5	44.	44.	1.84	.993	M/P	.591+02
MMH	172	UNLIKE-DOUBLET	.024	.020	24.	60.	201.	53.2	62.7	44.	44.	1.66	1.215	M/P	.640+02
MMH	173	UNLIKE-DOUBLET	.024	.020	24.	60.	192.	71.0	77.5	50.	50.	1.63	1.287	MIX	.779+02
MMH	174	UNLIKE-DOUBLET	.024	.020	24.	60.	97.	52.3	102.0	48.	48.	1.62	1.262	M/S	.108+03
MMH	175	UNLIKE-DOUBLET	.024	.020	24.	60.	97.	52.3	75.7	50.	50.	1.63	1.262	MIX	.203+03
MMH	176	UNLIKE-DOUBLET	.024	.020	24.	60.	97.	52.2	74.4	48.	48.	1.63	1.219	MIX	.184+03
MMH	177	UNLIKE-DOUBLET	.024	.020	24.	60.	97.	49.4	72.6	47.	48.	1.63	1.210	MIX	.178+03
MMH	178	UNLIKE-DOUBLET	.024	.020	24.	60.	97.	52.2	75.0	64.	68.	1.65	1.244	MIX	.369+03
MMH	179	UNLIKE-DOUBLET	.024	.020	24.	60.	97.	49.4	69.6	64.	68.	1.67	1.244	MIX	.369+03
MMH	180	UNLIKE-DOUBLET	.024	.020	24.	60.	202.	49.4	69.6	66.	71.	1.70	1.198	MIX	.193+03

TABLE B-II (cont.)

HYPERGOLIC STREAM IMPINGMENT DATA COMPILATION

INVESTIGATOR   LAWVER

FUEL TYPE	TEST NO.	MODE	PC (PSIA)	VAVG	WEF	NEO	REF	MED	DELTT (DEG F)	RELF	RELO	PPF (PSIA)	PPO (PSIA)	MRVP	XP	XO	XP	RESID
MMH	181	UNOFF	81.	115.	13.6	9.7	.221+05	.612+05	0.	.53+06	.15+07	.7	13.3	41.2	.0114529	.0114529	.53-08	.81+03
MMH	182	MIX	119.	109.	18.3	12.8	.216+05	.583+05	201.	.52+06	.14+07	.7	14.2	36.7	.0122358	.0122358	.55-08	.59+03
MMH	183	UNOFF	129.	41.	3.1	1.7	.863+04	.206+05	81.	.21+06	.49+06	.7	13.8	37.9	.0138413	.0138413	.65-08	.21+03
MMH	184	UNOFF	154.	48.	3.9	2.6	.HH7+04	.228+05	78.	.21+06	.55+06	.7	13.8	37.9	.0043086	.0043086	.64-08	.18+01
MMH	185	SEP	152.	104.	20.6	15.2	.216+05	.563+05	182.	.49+06	.14+07	.7	14.2	36.7	.0017771	.0017771	.55-08	.41+03
MMH	186	SEP	198.	108.	26.9	20.0	.216+05	.577+05	198.	.52+06	.14+07	.7	14.2	38.7	.0021417	.0021417	.56-08	.37+03
MMH	187	SEP	258.	100.	32.8	23.8	.104+05	.541+05	326.	.47+06	.13+07	.7	14.2	37.3	.0018273	.0018273	.64-08	.25+03
MMH	148	MIX	102.	46.	2.9	1.8	.217+05	.237+05	114.	.23+06	.57+06	.8	14.5	36.6	.0106627	.0106627	.55-08	.30+03
MMH	149	MIX	99.	107.	14.2	10.3	.217+05	.576+05	161.	.52+06	.14+07	.8	14.8	37.3	.0106176	.0106176	.57-08	.74+03
MMH	150	SEP	297.	104.	42.7	31.4	.214+05	.582+05	679.	.51+06	.15+07	.8	14.6	37.3	.0019809	.0019809	.56-08	.25+03
MMH	151	SEP	464.	111.	75.9	57.3	.223+05	.610+05	940.	.54+06	.17+07	.9	14.6	38.3	.0019785	.0019785	.66-08	.16+01
MMH	152	SEP	956.	120.	175.5	134.3	.252+05	.688+05	1342.	.60+06	.17+07	.9	18.-	38.0	.001H327	.001H327	—	.17+03
MMH	153	M/P	98.	38.	2.5	1.3	.719+04	.173+05	119.	.17+06	.41+06	.5	10.-	38.0	.0132176	.0132176	.49-08	.13+03
MMH	154	M/P	100.	30.	1.9	1.0	.592+04	.174+05	158.	.14+06	.42+06	.5	9.8	37.9	.0135005	.0135005	.48-08	.16+01
MMH	155	M/P	102.	42.	2.2	1.7	.718+04	.216+05	170.	.17+06	.52+06	.5	9.8	39.0	.0046772	.0046772	.46-08	.22+03
MMH	156	MIX	107.	60.	5.1	3.1	.108+05	.291+05	86.	.26+06	.70+06	.5	9.5	37.8	.0036548	.0036548	.42-08	.24+03
MMH	157	MIX	102.	63.	5.2	3.5	.111+05	.316+05	86.	.27+06	.76+06	.6	9.5	37.8	.0032796	.0032796	.41-08	.13+03
MMH	158	M/P	101.	31.	1.0	1.0	.519+04	.175+05	171.	.12+06	.44+06	.6	11.-	39.2	.0137980	.0137980	.54-08	.16+01
MMH	159	M/P	99.	35.	1.5	1.9	.624+04	.1H3+05	176.	.15+06	.47+06	.6	10.7	38.2	.0133728	.0133728	.52-08	.20+03
MMH	160	M/P	101.	46.	2.6	1.9	.824+04	.236+05	145.	.20+06	.57+06	.6	10.7	36.2	.0144912	.0144912	.49-08	.20+03
MMH	161	M/P	102.	46.	2.4	2.1	.H49+04	.228+05	131.	.20+06	.55+06	.6	10.7	38.2	.0145415	.0145415	.50-08	.31+03
MMH	162	MIX	107.	69.	5.4	3.0	.787+04	.249+05	145.	.19+06	.60+06	.6	10.7	38.2	.0144568	.0144568	.49-08	.25+03
MMH	163	MIX	98.	58.	4.2	3.0	.164+05	.306+05	94.	.30+06	.85+06	.5	10.4	38.-	.0129100	.0129100	.45-08	.39+01
MMH	164	MIX	100.	84.	8.4	9.1	.154+05	.434+05	85.	.75+06	.72+06	.5	10.4	38.1	.0134411	.0134411	.46-08	.24+03
MMH	165	MIX	95.	104.	13.9	3.3	.184+05	.552+05	72.	.37+06	.10+07	.5	10.4	36.1	.0122672	.0122672	.43-08	.24+03
MMH	166	M/P	99.	60.	4.5	3.1	.105+05	.306+05	79.	.46+06	.13+07	.5	10.1	39.1	.0117894	.0117894	.44-08	.24+03
MMH	167	MIX	99.	60.	4.3	3.2	.106+05	.307+05	65.	.25+06	.73+06	.5	10.1	39.1	.0135572	.0135572	.44-08	.24+03
MMH	168	MIX	95.	81.	4.5	3.0	.9a1+04	.308+05	65.	.23+06	.74+06	.5	10.-	42.2	.0133346	.0133346	.33-08	.16+03
MMH	169	UNOFF	89.	132.	19.0	13.0	.206+05	.654+05	75.	.49+06	.74+06	.5	7.4	42.2	.0071270	.0071270	.29-08	.37+03
MMH	170	M/P	95.	130.	19.0	13.5	.202+05	.649+05	102.	.23+06	.16+07	.4	7.4	42.2	.0013595	.0013595	.35-08	.34+03
MMH	171	M/P	196.	49.	5.2	4.5	.721+04	.262+05	106.	.48+06	.63+06	.4	7.4	42.2	.0014737	.0014737	.31-08	.59+02
MMH	172	M/P	198.	51.	0.2	4.5	.7H6+04	.258+05	76.	.17+06	.62+06	.4	7.4	42.2	.0027065	.0027065	.35-08	.78+02
MMH	173	M/P	201.	62.	9.6	1.2	.972+04	.310+05	67.	.19+06	.74+06	.4	7.4	39.7	.0020724	.0020724	.31-08	.11+01
MMH	175	M/S	192.	83.	16.1	3.1	.129+05	.415+05	116.	.23+06	.10+07	.4	8.6	38.9	.0022351	.0022351	.32-08	.20+03
MMH	176	MIX	97.	61.	4.5	2.9	.101+05	.304+05	63.	.31+06	.73+06	.4	4.2	38.-	.0027430	.0027430	.37-08	.37+03
MMH	177	MIX	97.	50.	4.3	2.9	.955+04	.305+05	82.	.24+06	.71+06	.4	6.0	36.9	.0032118	.0032118	.36-08	.18+03
MMH	178	MIX	97.	61.	4.1	3.3	.120+05	.294+05	69.	.23+06	.70+06	.4	12.9	34.2	.0033246	.0033246	.15-08	.39+03
MMH	180	MIX	202.	57.	6.1	6.3	.115+05	.312+05	110.	.28+06	.75+06	.6	11.5	32.2	.0024881	.0024881	.55-08	.19+03

TABLE B-II (cont.)

HYPERGOLIC STREAM IMPINGMENT DATA COMPILATION

INVESTIGATOR LANVFR

FUEL TYPE	TEST NO.	INJECTOR TYPE	DO (IN)	DF (IN)	L/D	IMP ANGLE (DEG)	PC (PSIA)	VO (FT/S)	VF (FT/S)	TO (F)	TF (F)	MR	MF/MO	MODE	REACT (SEC)
MMH	1A1	UNLIKE-DOUBLET	.024	.020	24.	60.	295.	50.4	75.1	67.	73.	1.60	1.337	MIX	.152+03
MMH	1A2	UNLIKE-DOUBLET	.024	.020	24.	60.	182.	108.8	159.2	75.	78.	1.62	1.295	SEP	.651+03
MMH	1A3	UNLIKE-DOUBLET	.024	.020	24.	60.	198.	102.6	150.6	76.	77.	1.62	1.305	SEP	.560+03
MMH	1A4	UNLIKE-DOUBLET	.024	.020	24.	60.	259.	108.2	108.9	71.	70.	1.57	1.380	SEP	.243+03
MMH	1A5	UNLIKE-DOUBLET	.024	.020	24.	60.	262.	72.2	99.8	70.	70.	1.64	1.272	UNDEF	.211+03
MMH	1A6	UNLIKE-DOUBLET	.024	.020	24.	60.	262.	50.4	79.3	69.	69.	1.51	1.498	MIX	.171+03
MMH	1A7	UNLIKE-DOUBLET	.024	.020	24.	60.	293.	44.2	62.5	68.	70.	1.58	1.207	MIX	.116+03
MMH	1A8	UNLIKE-DOUBLET	.024	.020	24.	60.	300.	53.9	80.9	70.	70.	1.58	1.364	M/S	.154+03
MMH	1A9	UNLIKE-DOUBLET	.024	.020	24.	60.	295.	89.7	135.6	73.	72.	1.57	1.366	SEP	.288+03
MMH	190	UNLIKE-DOUBLET	.024	.020	24.	60.	99.	50.7	74.5	64.	82.	1.64	1.292	MIX	.535+03
MMH	191	UNLIKE-DOUBLET	.024	.020	24.	60.	98.	51.8	77.0	62.	93.	1.64	1.302	MIX	.692+03
MMH	192	UNLIKE-DOUBLET	.024	.020	24.	60.	98.	51.6	76.5	71.	149.	1.69	1.258	M/S	.233+04
MMH	193	UNLIKE-DOUBLET	.024	.020	24.	60.	99.	51.5	76.4	78.	177.	1.70	1.254	M/S	.410+04
MMH	194	UNLIKE-DOUBLET	.024	.020	24.	60.	79.	53.0	74.5	80.	200.	1.73	1.236	M/S	.630+04
MMH	195	UNLIKE-DOUBLET	.024	.020	24.	60.	202.	49.6	71.9	82.	196.	1.77	1.173	SEP	.271+04
MMH	196	UNLIKE-DOUBLET	.024	.020	24.	60.	202.	43.3	70.6	124.	178.	1.69	1.214	SEP	.324+04
MMH	197	UNLIKE-DOUBLET	.024	.020	24.	60.	202.	43.3	67.7	112.	89.	1.69	1.169	MIX	.486+03
A-50	198	UNLIKE-DOUBLET	.024	.020	24.	60.	92.	36.6	51.6	53.	60.	1.64	1.234	M/P	.275+03
A-50	199	UNLIKE-DOUBLET	.024	.020	24.	60.	94.	45.4	66.5	74.	85.	1.58	1.337	UNDEF	.761+03
A-50	200	UNLIKE-DOUBLET	.024	.020	24.	60.	89.	50.3	72.7	65.	75.	1.60	1.297	MIX	.641+03
A-50	201	UNLIKE-DOUBLET	.024	.020	24.	60.	97.	52.6	76.5	68.	73.	1.59	1.319	MI.	.617+03
A-50	202	UNLIKE-DOUBLET	.024	.020	24.	60.	81.	79.4	114.2	69.	74.	1.61	1.277	MI.	.114+04
A-50	203	UNLIKE-DOUBLET	.024	.020	24.	60.	102.	90.3	127.2	72.	72.	1.63	1.241	MIX	.100+04
A-50	204	UNLIKE-DOUBLET	.024	.020	24.	60.	95.	111.3	157.2	70.	70.	1.63	1.246	MIX	.125+04
A-50	205	UNLIKE-DOUBLET	.024	.020	24.	60.	201.	41.2	49.7	66.	68.	1.91	.907	M/P	.172+03
A-50	206	UNLIKE-DOUBLET	.024	.020	24.	60.	199.	41.5	70.6	77.	69.	1.67	1.179	MIX	.207+03
A-50	207	UNLIKE-DOUBLET	.024	.020	24.	60.	193.	114.1	102.0	80.	81.	1.61	1.266	SEP	.884+03
A-50	208	UNLIKE-DOUBLET	.024	.020	24.	60.	295.	44.9	64.9	70.	74.	1.60	1.291	MIX	.174+03
A-50	209	UNLIKE-DOUBLET	.024	.020	24.	60.	293.	43.6	64.1	63.	63.	1.57	1.351	MIX	.133+03
A-50	21	UNLIKE-DOUBLET	.024	.020	24.	60.	290.	42.8	67.5	61.	64.	1.62	1.265	MIX	.123+03
A-50	211	UNLIKE-DOUBLET	.024	.020	24.	60.	293.	51.7	76.5	62.	84.	1.47	1.542	MIX	.154+03
A-50	212	UNLIKE-DOUBLET	.024	.020	24.	60.	290.	74.2	106.1	78.	79.	1.61	1.269	M/S	.291+03
A-50	213	UNLIKE-DOUBLET	.024	.020	24.	60.	289.	90.8	130.7	76.	77.	1.60	1.282	SEP	.355+03
A-50	214	UNLIKE-DOUBLET	.024	.020	24.	60.	293.	112.8	103.2	75.	77.	1.59	1.295	SEP	.410+03
A-50	215	UNLIKE-DOUBLET	.024	.020	24.	60.	292.	72.3	104.2	71.	75.	1.59	1.306	SEP	.470+03
A-50	216	UNLIKE-DOUBLET	.024	.020	24.	60.	289.	92.6	133.4	66.	70.	1.60	1.296	SEP	.157+03
A-50	217	UNLIKE-DOUBLET	.024	.020	24.	60.	491.	44.0	56.8	68.	68.	1.60	1.292	SEP	.193+03
MMH	218	XDT1	.024	.021	0.	0.	135.	92.6	63.5	65.	70.	1.67	1.005	MIX	.238+03
MMH	219	XDT1	.024	.021	0.	0.	124.	50.3	52.6	72.	73.	1.70	.967	MIX	.341+03
MMH	220	XDT1	.024	.021	0.	0.	98.	39.9	52.6	69.	71.	1.63	1.052	MIX	.327+03

TABLE B-II (cont.)

HYPERGOLIC STREAM IMPINGMENT DATA COMPILATION

INVESTIGATOR LAWVER

FUEL TYPE	TEST NO.	MODE	PC (PSIA)	VAVG	WEF	WEO	PEF	RED	DELTI (DEG F)	RELF	RELO	PPF (PSIA)	PPO (PSIA)	MRVP	XF	XO	XP	RESID
MMH	181	MIX	295.	60.	13.8	9.6	.126+05	.320+05	128.	.30+06	.77+06	.9	13.8	30.8	.0034897	.0034897	.57-08	.15+03
MMH	182	SEP	147.	128.	38.7	28.7	.280+05	.723+05	129.	.67+06	.17+07	1.1	16.9	32.0	.0110102	.0110102	.59-08	.65+01
MMH	183	SEP	198.	121.	37.0	27.9	.243+05	.666+05	129.	.63+06	.16+07	1.0	17.3	33.7	.0111643	.0111643	.62-08	.56+04
MMH	184	SEP	259.	86.	25.2	17.6	.178+05	.469+05	141.	.43+06	.11+07	.8	15.2	37.0	.0015223	.0011643	.61-08	.24+03
MMH	185	UNOFF	209.	81.	22.2	16.6	.163+05	.444+05	141.	.39+06	.11+07	.8	14.8	36.0	.0015223	.0015223	.59-08	.21+03
MMH	186	MIX	262.	62.	13.7	6.6	.130+05	.324+05	101.	.31+06	.78+06	.8	14.5	35.4	.00 4722	.0040248	.61-08	.17+03
MMH	187	MIX	293.	51.	16.0	7.4	.172+05	.242+05	95.	.24+06	.68+06	.8	14.2	35.9	.0040248	.0033121	.62-08	.12+03
MMH	188	SEP	100.	64.	16.3	11.3	.172+05	.348+05	108.	.32+06	.84+06	.8	14.8	36.0	.0033121	.0019571	.61-08	.15+03
MMH	189	SEP	295.	108.	45.0	31.3	.226+05	.589+05	140.	.54+06	.14+07	.9	16.0	36.4	.0019571	.0174107	.50-08	.29+03
MMH	190	MIX	99.	60.	4.0	3.2	.136+05	.317+05	61.	.33+06	.76+06	1.2	12.7	22.6	.0174107	.0232494	.39-08	.54+03
MMH	191	MIX	98.	61.	5.0	3.3	.154+05	.521+05	49.	.37+06	.77+06	1.0	12.9	16.2	.0232494	.0731361	.20-08	.69+03
MMH	192	S/S	99.	61.	5.4	3.4	.229+05	.336+05	40.	.55+06	.81+06	6.5	15.2	5.3	.0731361	.1234444	.21-08	.23+04
MMH	193	S/S	98.	62.	6.8	3.8	.275+05	.344+05	27.	.66+06	.84+06	12.0	18.1	3.6	.1234444	.1433715	.22-08	.1+04
MMH	194	SEP	203.	58.	10.0	7.0	.377+05	.303+05	18.	.79+06	.87+06	19.1	20.0	2.4	.1433715	.0925356	.23-08	.03+04
MMH	195	SEP	202.	58.	10.2	6.8	.292+05	.346+05	54.	.70+06	.83+06	17.6	20.9	9.5	.0925356	.0426073	.11-07	.27+04
MMH	196	SEP	232.	56.	7.0	6.0	.247+05	.457+05	69.	.62+06	.10+07	12.2	52.2	56.0	.0426073	.0125927	.19-07	.12+04
A-50	197	MIX	232.	42.	2.3	1.5	.695+04	.408+05	115.	.31+06	.98+06	1.4	30.5	15.1	.0125927	.0143764	.30-08	.49+03
A-50	198	MIX	94.	54.	4.0	2.0	.108+05	.216+05	89.	.17+06	.52+06	2.1	9.5	15.0	.0143764	.03 3722	.46-08	.28+03
A-50	199	UNOFF	89.	59.	5.1	3.1	.113+05	.300+05	109.	.26+06	.72+06	2.0	13.2	14.2	.03 3722	.02 4571	.37-08	.76+03
A-50	200	MIX	97.	62.	5.1	6.7	.170+05	.316+05	143.	.27+06	.76+06	2.0	14.2	15.8	.02 4571	.02 3521	.42-08	.64+01
A-50	201	MIX	102.	93.	10.1	10.5	.186+05	.512+05	145.	.41+06	.81+06	2.9	15.6	16.2	.02 3521	.02 5272	.47-08	.62+03
A-50	202	M/P	95.	104.	15.3	15.3	.227+05	.589+05	149.	.45+06	.12+07	1.9	15.8	17.5	.02 5272	.02 5235	.42-08	.11+04
A-50	203	MIX	201.	129.	22.7	4.7	.767+04	.719+05	155.	.54+06	.14+07	1.8	13.9	17.5	.02 5235	.01 4752	.45-08	.10+04
A-50	204	M/P	199.	49.	4.7	7.1	.101+05	.260+05	172.	.17+06	.17+07	1.8	17.7	21.2	.01 4752	.01 4864	.45-08	.12+04
A-50	205	MIX	193.	50.	44.9	34.4	.254+05	.547+05	141.	.24+06	.83+06	2.4	19.0	17.5	.01 4864	.01 5149	.53-08	.17+03
A-50	206	SEP	293.	132.	11.8	7.7	.460+04	.741+05	202.	.61+06	.19+07	2.0	14.8	16.1	.01 5149	.01 4598	.76-08	.29+03
A-50	207	MIX	291.	52.	11.1	6.7	.841+04	.290+05	202.	.23+06	.70+06	1.5	12.0	18.0	.01 4598	.01 4657	.43-08	.68+03
A-50	208	MIX	293.	49.	10.1	6.5	.450+04	.271+05	202.	.21+06	.65+06	1.8	12.6	18.7	.01 4657	.01 4549	.39-08	.18+03
A-50	209	MIX	290.	51.	12.6	4.7	.960+04	.259+05	272.	.20+06	.62+06	2.6	12.3	15.5	.01 4549	.01 4631	.38-08	.13+03
A-50	210	MIX	290.	87.	10.4	11.3	.125+05	.305+05	391.	.30+06	.87+06	2.3	18.1	15.5	.01 4631	.01 4850	.53-08	.12+03
A-50	211	M/S	289.	106.	31.1	21.3	.154+05	.496+05	242.	.39+06	.12+07	2.1	17.3	16.9	.01 4850	.01 4800	.52-08	.15+03
A-50	212	SEP	293.	132.	48.1	32.5	.199+05	.604+05	132.	.48+06	.14+07	1.9	16.9	17.1	.01 4800	.01 5081	.49-08	.35+03
A-50	213	SEP	292.	85.	74.0	46.6	.244+05	.733+05	379.	.59+06	.16+07	1.9	15.2	16.2	.01 5081	.01 4720	.41-08	.41+03
A-50	214	SEP	291.	108.	50.7	32.9	.150+05	.402+05	493.	.30+06	.11+07	1.9	14.2	16.6	.01 4720	.00 4841	.43-08	.47+03
A-50	215	SEP	291.	108.	81.5	54.4	.196+05	.502+05	742.	.46+06	.14+07	.8	13.2	17.6	.00 4841	.01 4698	.43-08	.16+03
A-50	217	SEP	491.	47.	5.8	3.3	.476+04	.274+05	214.	.98+06	.28+04	.8	15.6	32.6	.01 4698	.01 4973	.90-10	.19+03
MMH	218	MIX	135.	55.	4.4	4.1	.112+05	.328+05	209.	.11+04	.33+04	.9	15.6	34.4	.01 4973	.01 4863	.99-10	.24+03
MMH	219	MIX	124.	45.	2.4	2.0	.913+04	.256+05	183.	.91+03	.26+04	.8	14.5	34.2	.01 4863		.10-09	.34+03
MMH	220	MIX	98.															.33+03

TABLE B-II (cont.)

HYPERGOLIC STREAM IMPINGMENT DATA COMPILATION

INVESTIGATOR LANVER

FUEL TYPE	TEST NO.	INJECTOR TYPE	DN (IN)	DF (IN)	L/D	IMP ANGLE (DEG)	PC (PSIA)	VO (FT/S)	VF (FT/S)	TO (F)	TF (F)	MR	MF/MO	MODE	REACT (SEC)
MMH	221	XDT1	.024	.021	0.	0.	81.	32.6	42.6	62.	68.	1.66	1.024	MIX	.271+01
MMH	222	XDT1	.024	.021	0.	0.	146.	59.7	76.1	76.	75.	1.69	.986	SEP	.379+03
MMH	223	XDT1	.024	.021	0.	0.	194.	79.1	100.7	79.	97.	1.71	.975	SEP	.651+03
MMH	224	XDT1	.024	.021	0.	0.	122.	50.6	63.8	77.	141.	1.77	.930	MIX	.151+04
MMH	225	XDT1	.024	.021	0.	0.	123.	51.3	64.4	80.	164.	1.80	.909	MIX	.236+04
MMH	226	XDT1	.024	.021	0.	0.	122.	51.2	66.0	93.	229.	1.82	.925	SEP	.803+04
MMH	227	XDT1	.024	.021	0.	0.	122.	51.9	66.7	116.	242.	1.81	.929	SEP	.125+05
MMH	228	XDT1	.024	.021	0.	0.	144.	61.9	78.7	127.	249.	1.80	.928	SEP	.158+05
MMH	229	XDT1	.024	.021	0.	0.	119.	53.0	71.1	109.	245.	1.75	1.001	SEP	.133+05
MMH	230	XDT1	.024	.021	0.	0.	122.	56.1	70.5	120.	268.	1.75	1.011	SEP	.200+05
MMH	231	XDT1	.024	.021	0.	0.	136.	62.2	83.6	126.	280.	1.76	.999	SEP	.272+05
MMH	232	XDT1	.024	.021	0.	0.	145.	63.7	86.0	162.	291.	1.72	1.022	SEP	.420+05
MMH	233	XDT1	.024	.021	0.	0.	124.	53.3	73.3	153.	285.	1.69	1.060	SEP	.357+05
MMH	234	SPLASH PLATE	.024	.021	0.	90.	123.	48.9	62.7	73.	76.	1.69	.996	M/S	.371+03
MMH	235	SPLASH PLATE	.024	.021	0.	90.	102.	37.4	48.2	71.	72.	1.69	.983	MIX	.303+03
MMH	236	SPLASH PLATE	.024	.021	0.	90.	81.	31.8	40.8	74.	76.	1.68	.997	M/P	.371+03
MMH	237	SPLASH PLATE	.024	.021	0.	90.	144.	52.8	76.8	78.	82.	1.68	.999	SEP	.472+03
MMH	238	SPLASH PLATE	.024	.041	0.	90.	164.	63.2	104.2	74.	74.	1.65	1.027	SEP	.474+03
MMH	239	SPLASH PLATE	.024	.021	0.	90.	162.	53.2	70.1	74.	74.	1.64	1.052	M/S	.300+03
MMH	240	SPLASH PLATE	.024	.021	0.	90.	160.	55.5	71.9	77.	70.	1.66	1.018	M/S	.366+01
MMH	241	SPLASH PLATE	.024	.021	0.	90.	192.	53.4	66.9	78.	71.	1.67	1.001	M/S	.281+03
MMH	242	SPLASH PLATE	.024	.021	0.	90.	192.	74.0	105.2	79.	75.	1.64	1.036	SEP	.406+01
MMH	243	SPLASH PLATE	.024	.021	0.	90.	123.	49.0	66.3	85.	170.	1.72	1.015	SEP	.269+04
MMH	244	SPLASH PLATE	.024	.021	0.	90.	117.	51.6	71.5	136.	239.	1.72	1.054	SEP	.934+04
MMH	245	SPLASH PLATE	.024	.021	0.	90.	119.	52.4	75.1	132.	288.	1.70	1.069	SLP	.322+05
MMH	246	SPLASH PLATE	.024	.021	0.	90.	139.	61.1	68.0	132.	283.	1.60	1.086	SLP	.503+05
MMH	247	SPLASH PLATE	.024	.021	0.	90.	137.	60.7	89.0	153.	286.	1.69	1.058	SEP	.406+05
MMH	248	SPLASH PLATE	.024	.021	0.	90.	147.	61.4	84.8	154.	287.	1.69	1.068	SEP	.300+05
MMH	249	TRIPLET	.050	.029	4.	32.	124.	48.1	51.4	73.	75.	2.15	2.816	MIX	.802+01
MMH	250	TRIPLET	.050	.029	4.	32.	125.	49.7	48.8	70.	75.	2.37	2.332	MIX	.747+03
MMH	251	TRIPLET	.050	.029	4.	32.	99.	38.5	38.6	68.	78.	2.31	2.424	MIX	.705+03
MMH	252	TRIPLET	.050	.029	4.	32.	80.	31.7	30.6	72.	78.	2.41	2.259	MIX	.810+03
MMH	253	TRIPLET	.050	.029	4.	32.	146.	54.1	63.4	72.	76.	2.13	2.879	SEP	.875+03
MMH	254	TRIPLET	.040	.029	4.	32.	194.	70.0	71.8	71.	69.	2.28	2.503	SEP	.665+03
MMH	255	TRIPLET	.050	.029	4.	32.	119.	52.1	51.6	77.	178.	2.23	2.749	MIX	.762+04
MMH	256	TRIPLET	.050	.029	4.	32.	115.	53.8	61.5	76.	249.	2.27	2.828	M/S	.220+05
MMH	257	TRIPLET	.050	.029	4.	32.	116.	50.7	54.6	100.	312.	1.90	4.059	SEP	.144+06
MMH	258	TRIPLET	.050	.029	4.	32.	131.	65.3	74.6	120.	300.	2.31	2.796	SEP	.426+06
MMH	259	TRIPLET	.050	.029	4.	32.	137.	64.4	71.2	153.	301.	2.30	2.697	SEP	.108+06
MMH	260	SMALL TRIPLET	.034	.020	8.	32.	126.	50.4	67.5	59.	71.	1.76	4.279	M/P	.548+03

TABLE B-II (cont.)

HYPERGOLIC STREAM IMPINGMENT DATA COMPILATION

INVESTIGATOR LAWVER

FUEL TYPE	TEST NO.	MODE	PC (PSIA)	VAVG	MEF	MEO	REF	REU	DELTI (DEG F)	RELF	RELO	PPF (PSIA)	PPO (PSIA)	MRVP	XF	XO	XP	REBID
MMH	221	MIX	81.	36.	1.3	1.1	.71E+04	.202+05	165.	.72+03	.20+04	.8	12.3	32.7	.01	4913.	.98-10	.27+03
MMH	222	SFP	148.	66.	7.5	7.1	.137+05	.399+05	229.	.14+04	.40+04	1.0	17.3	35.6	.01	4997.	.10-09	.38+03
MMH	223	SFP	198.	68.	17.9	16.5	.218+05	.538+05	221.	.22+04	.54+04	1.8	16.6	21.2	.01	4977.	.63-10	.65+03
MMH	224	MIX	122.	55.	4.9	4.2	.100+05	.340+05	158.	.19+04	.34+04	5.3	17.7	7.5	.04	4954.	.45-10	.15+04
MMH	225	MIX	123.	56.	5.2	4.4	.224+05	.351+05	137.	.22+04	.35+04	8.8	19.0	5.0	.07	4964.	.37-10	.24+04
MMH	226	SFP	122.	56.	6.5	4.7	.305+05	.340+05	92.	.34+04	.38+04	30.9	26.2	2.1	.25	5008.	.46-10	.80+04
MMH	227	SFP	122.	57.	6.5	5.5	.377+05	.438+05	82.	.38+04	.44+04	37.0	44.0	2.0	.30	5031.	.68-10	.13+05
MMH	228	SFP	140.	68.	10.9	9.7	.464+05	.548+05	87.	.46+04	.55+04	42.1	56.5	3.2	.29	5072.	.74-10	.16+05
MMH	229	SFP	119.	60.	7.3	5.4	.409+05	.432+05	77.	.41+04	.41+04	39.3	37.8	2.1	.33	4716.	.60-10	.13+05
MMH	230	SFP	122.	59.	11.	5.7	.467+05	.442+05	42.	.47+04	.45+04	56.8	48.5	1.7	.47	4972.	.91-10	.20+05
MMH	231	SFP	146.	70.	13.4	10.5	.504+05	.586+05	46.	.59+04	.59+04	65.9	68.5	3.7	.45	5062.	.13-09	.27+05
MMH	232	SFP	145.	72.	14.5	13.7	.654+05	.704+05	40.	.65+04	.70+04	74.7	116.0	1.1	.52	4903.	.14-09	.42+05
MMH	233	SFP	124.	61.	8.0	7.0	.578+05	.554+05	30.	.54+04	.56+04	69.7	97.1	1.1	.56	5031.	.13-09	.38+05
MMH	234	M/S	123.	58.	2.1	1.9	.144+04	.321+05	195.	.11+04	.32+04	1.0	16.2	32.5	.01	5049.	.10-09	.37+03
MMH	236	MIX	107.	42.	1.2	1.0	.186+05	.240+05	196.	.84+03	.25+04	1.0	15.2	34.0	.01	5412.	.11-09	.10+03
MMH	237	M/P	81.	35.	7.5	7.0	.740+04	.210+05	178.	.74+03	.21+04	1.2	16.5	33.0	.01	5119.	.13-09	.37+03
MMH	238	SFP	160.	66.	8.9	7.8	.107+05	.404+05	178.	.15+04	.40+04	.9	18.6	31.0	.01	4851.	.91-10	.47+03
MMH	239	M/S	100.	69.	17.0	16.2	.144+05	.545+05	178.	.14+04	.55+04	1.0	16.5	35.0	.01	6126.	.10-09	.47+03
MMH	240	M/S	100.	67.	7.0	6.2	.125+05	.351+05	149.	.12+04	.35+04	1.1	17.7	32.6	.01	5765.	.10-09	.30+05
MMH	241	M/S	166.	67.	7.3	8.0	.174+05	.373+05	162.	.13+04	.37+04	1.0	18.1	32.1	.01	5254.	.12-09	.37+03
MMH	242	MIX	192.	58.	17.9	8.0	.119+05	.301+05	149.	.12+04	.30+04	1.0	18.1	37.2	.01	4857.	.92-10	.41+03
MMH	243	SFP	125.	56.	14.7	16.2	.186+05	.534+05	214.	.19+04	.53+04	1.0	18.6	4.9	.08	5008.	.35-10	.29+04
MMH	244	SFP	117.	59.	7.3	5.2	.240+05	.359+05	113.	.24+04	.34+04	35.1	21.0	1.6	.30	4639.	.44-10	.93+04
MMH	245	SFP	110.	65.	7.7	7.3	.397+05	.364+05	79.	.40+04	.49+04	72.0	67.5	2.3	.49	4667.	.85-10	.32+05
MMH	246	M/S	137.	74.	14.5	10.1	.642+05	.581+05	44.	.64+04	.54+04	68.2	87.5	3.3	.53	5180.	.13-09	.20+05
MMH	247	SFP	160.	66.	14.1	12.4	.645+05	.677+05	43.	.66+04	.68+04	72.0	97.1	3.3	.48	5260.	.13-09	.36+05
MMH	248	SFP	160.	63.	17.1	12.0	.679+05	.646+05	44.	.63+04	.65+04	71.2	99.1	33.2	.01	4944.	.39-08	.60+03
MMH	249	MIX	129.	66.	17.1	6.1	.131+05	.652+05	44.	.50+05	.26+06	16.0	16.0	30.0	.01	5020.	.34-08	.75+03
MMH	250	M/P	125.	63.	14.7	3.9	.100+05	.507+05	44.	.49+05	.26+06	14.2	14.2	27.8	.01	5020.	.37-08	.78+03
MMH	251	MIX	99.	60.	7.7	2.2	.795+04	.427+05	44.	.40+05	.20+06	1.1	15.6	29.8	.01	4790.	.45-10	.81+03
MMH	252	MIX	146.	80.	28.7	13.1	.162+05	.742+05	44.	.32+05	.17+06	1.1	15.2	31.5	.01	4926.	.11-07	.88+03
MMH	253	MIX	194.	101.	57.2	30.7	.186+05	.103+06	44.	.65+05	.31+06	.8	15.2	38.3	.00	4435.	.10-08	.66+04
MMH	255	SFP	110.	72.	23.3	9.0	.308+05	.722+05	44.	.75+05	.41+06	12.2	17.7	3.3	.10	4207.	.17-08	.76+04
MMH	256	M/S	116.	75.	29.4	9.3	.494+05	.741+05	44.	.12+06	.29+06	38.5	17.3	1.9	.33	5868.	.12-07	.24+06
MMH	257	MIX	113.	71.	64.0	14.7	.186+05	.113+06	44.	.20+06	.30+06	100.6	74.1	1.6	.89	4082.	.89-08	.14+06
MMH	258	S/C	131.	91.	56.0	19.8	.840+05	.116+06	44.	.37+06	.45+06	65.0	48.2	1.5	.65	4463.	.15-07	.63+05
MMH	259	SFP	157.	88.	54.2	25.4	.810+05	.139+06	44.	.32+06	.56+06	67.0	97.1	2.8	.64	4082.	.12-07	.11+06
MMH	275	M/P	126.	81.	18.9	5.5	.111+05	.429+05	44.	.45+05	.17+06	.8	11.4	27.3	.01	5204.	.10-08	.55+03

TABLE B-II (cont.)

HYPERGOLIC STREAM IMPINGMENT DATA COMPILATION

INVESTIGATOR LAWVER

FUEL TYPE	TEST NO.	INJECTOR TYPE	DO (IN)	DF (IN)	L/D	IMP ANGLE (DEG)	PC (PSIA)	VO (FT/S)	VF (FT/S)	TO (F)	TF (F)	MR	MF/MO	MODE	REACT (SEC)
MMH	276	SMALL TRIPLET	.034	.020	8.	32.	129.	47.0	65.9	78.	77.	1.66	4.760	MIX	.769+03
MMH	277	SMALL TRIPLET	.034	.020	8.	32.	101.	36.1	50.0	71.	80.	1.67	4.682	MIX	.736+03
MMH	278	SMALL TRIPLET	.034	.020	8.	32.	81.	30.5	38.7	71.	77.	1.84	3.867	MIX	.659+03
MMH	279	SMALL TRIPLET	.034	.020	8.	32.	157.	54.1	71.5	71.	75.	1.63	4.960	M/S	.650+03
MMH	280	SMALL TRIPLET	.034	.020	8.	32.	210.	72.2	102.7	72.	73.	1.64	4.896	SEP	.621+03
MMH	281	SMALL TRIPLET	.034	.020	8.	32.	129.	48.4	71.5	80.	150.	1.64	5.079	MIX	.377+04
MMH	282	SMALL TRIPLET	.034	.020	8.	32.	129.	48.8	74.5	85.	226.	1.66	5.163	M/S	.143+05
MMH	283	SMALL TRIPLET	.034	.020	8.	32.	132.	47.3	73.1	85.	250.	1.68	5.188	M/S	.191+05
MMH	284	SMALL TRIPLET	.034	.020	8.	32.	150.	49.3	76.0	130.	287.	1.66	5.211	SEP	.540+05
MMH	285	SMALL TRIPLET	.034	.020	8.	32.	156.	58.6	90.9	131.	206.	1.67	5.232	SEP	.613+05
MMH	286	SMALL TRIPLET	.034	.020	8.	32.	150.	61.3	95.0	145.	297.	1.66	5.280	SEP	.783+05
MMH	287	UNLIKE-DOUBLET	.024	.020	24.	60.	124.	49.2	72.5	72.	82.	1.63	1.309	MIX	.454+03
MMH	288	UNLIKE-DOUBLET	.024	.020	24.	60.	98.	39.3	57.6	73.	72.	1.62	1.299	M/P	.364+03
MMH	289	UNLIKE-DOUBLET	.024	.020	24.	60.	78.	32.5	50.1	75.	76.	1.54	1.439	M/P	.456+03
MMH	290	UNLIKE-DOUBLET	.024	.020	24.	60.	76.	31.2	48.6	74.	75.	1.62	1.294	M/P	.424+03
MMH	291	UNLIKE-DOUBLET	.024	.020	24.	60.	147.	50.9	84.5	75.	75.	1.66	1.241	MIX	.394+03
MMH	292	UNLIKE-DOUBLET	.024	.020	24.	60.	194.	78.9	113.9	76.	76.	1.65	1.265	M/S	.414+05
MMH	293	UNLIKE-DOUBLET	.024	.020	24.	60.	123.	50.7	76.7	76.	185.	1.68	1.293	SEP	.303+04
MMH	294	UNLIKE-DOUBLET	.024	.020	24.	60.	123.	51.0	76.5	76.	249.	1.74	1.282	SEP	.102+05
MMH	295	UNLIKE-DOUBLET	.024	.020	24.	60.	121.	53.0	82.4	80.	240.	1.65	1.360	SEP	.144+05
MMH	296	UNLIKE-TRIPLET	.024	.020	24.	60.	145.	64.5	99.4	116.	290.	1.71	1.296	SEP	.132+05
MMH	297	UNLIKE-DOUBLET	.024	.020	24.	60.	144.	66.6	104.6	131.	294.	1.65	1.371	SEP	.463+05

TABLE B-II (cont.)

HYPERGULIC STREAM IMPINGEMENT DATA COMPILATION

INVESTIGATOR LAWVER

FUEL TYPE	TEST NO.	MODE	PC (PSIA)	VAVG	WEF	WEO	PEF	REO	DELTI (DEG F)	RT_F	RELO	PPF (PSIA)(PSIA)	PPO (PSIA)	MRVP	XF	XO	XP	REBID
MMH	276	MTX	129.	79.	16.7	5.4	.115+05	.445+05	44.	.46+05	.18+06	1.0	18.1	35.2	.01	5695.	.17-06	.77+03
MMH	277	MTX	101.	60.	8.6	2.4	.900+04	.328+05	44.	.36+05	.13+06	1.1	15.2	27.6	.01	5780.	.15-08	.74+03
MMH	278	MTX	81.	87.	4.1	1.4	.615+04	.277+05	44.	.27+05	.11+06	1.0	15.2	29.8	.01	5672.	.17-08	.66+03
MMH	279	M/S	157.	93.	31.5	8.4	.173+05	.492+05	44.	.55+05	.20+06	1.0	15.6	31.6	.01	5922.	.13-08	.65+03
MMH	280	SEP	210.	121.	73.7	20.2	.173+05	.660+05	44.	.70+05	.26+06	.9	15.6	34.3	.05	5951.	.12-08	.62+01
MMH	281	MTX	129.	84.	25.1	5.6	.216+05	.463+05	44.	.65+05	.19+06	6.7	19.0	6.6	.05	5502.	.58-09	.30+04
MMH	282	M/S	129.	84.	31.7	6.0	.364+05	.482+05	44.	.15+06	.19+06	29.6	21.6	1.3	.23	5515.	.46-09	.14+05
MMH	283	M/S	132.	84.	33.0	6.8	.413+05	.467+05	44.	.17+06	.19+06	43.1	21.6	1.2	.33	5A35.	.72-09	.19+05
MMH	284	SEP	130.	8A.	30.3	8.1	.52+05	.627+05	44.	.21+06	.25+06	71.2	00.0	2.1	.55	5712.	.14-08	.54+05
MMH	285	SEP	156.	105.	67.4	13.9	.630+05	.751+05	44.	.27+06	.30+06	80.9	61.0	1.5	.52	5784.	.14-08	.61+05
MMH	286	SEP	150.	110.	70.8	16.1	.715+05	.855+05	44.	.29+06	.34+06	82.1	82.6	2.5	.55	5169.	.44-08	.78+05
MMH	287	MTX	124.	58.	5.5	3.9	.132+05	.121+05	44.	.32+06	.77+06	1.2	15.6	27.4	.01	4944.	.62-08	.46+03
MMH	288	M/S	96.	40.	2.7	2.0	.960+04	.254+05	44.	.23+06	.42+06	.9	16.0	36.4	.01	4954.	.76-08	.37+01
MMH	289	M/S	72.	39.	1.5	1.1	.672+04	.216+05	44.	.21+06	.52+06	1.0	16.0	31.8	.01	4665.	.74-08	.46+01
MMH	290	M/S	78.	39.	1.5	1.1	.472+04	.219+05	44.	.20+06	.53+06	1.0	16.5	30.0	.01	4901.	.64-08	.43+03
MMH	291	MTX	147.	64.	71.5	6.8	.1.4+05	.391+05	44.	.35+06	.94+06	1.0	17.1	34.0	.01	5009.	.19-08	.40+01
MMH	292	M/S	102.	92.	7.4	16.5	.197+05	.527+05	44.	.47+06	.13+07	14.0	16.9	2.9	.34	4922.	.32-08	.16+04
MMH	293	M/S	123.	69.	7.0	4.2	.201+05	.317+05	44.	.70+06	.64+06	42.3	16.0	1.2	.29	4720.	.48-08	.14+05
MMH	294	SEP	123.	81.	8.7	4.4	.438+05	.497+05	44.	.11+07	.11+07	35.5	44.4	1.0	.11	4718.	.65-08	.10+05
MMH	295	SEP	121.	60.	8.0	5.7	.716+05	.590+05	44.	.11+07	.14+07	73.5	61.6	2.1	.51	4718.	.65-08	.31+05
MMH	296	SEP	145.	77.	16.5	11.2	.716+05	.590+05	44.	.14+07	.14+07	73.5	61.6	2.1	.51	4720.	.65-08	.31+05
MMH	297	SEP	144.	81.	20.5	13.7	.772+05	.691+05	44.	.19+07	.17+07	78.4	95.1	3.0	.54	4624.	.93-08	.46+05

MAX TIME AMORT ADHE 020571 MUT1000000

M	000000 000001	000000 044714	000000 044714	000000 044715	000001 044715	000001 044705	000000 000001	000000 000008	000000 000001	000051 000273	000000 000010	000051 000100	000000 000000
	000000 000003	000001 044744	000001 044744	000001 000003	000100 020348	020330	044736	000000 000001	010000				
A	000016 044736	000000 060001	000000 060001	000000 000010	000000 000010	000000 0000	000010	777777	000000 000054	127000 000000			
	210000 000000	155018 142661	201406 000000	201406 000000	1460000 000000	000000	000000	000000 000306	000000 000001				
R	000000 000000	000000 000000	000000 000000	000000 000010	000102 044715	044715	000000 000000	000000 000000					
	000000 000000	000000 000000	000000 000000	000000 000000	230040 562300	777777	777776	777777 777776	777777 777776				

RUNSTREAM ANALYSIS TERMINATED

TABLE B-II (cont.)

HYPERGOLIC STREAM IMPINGMENT DATA COMPILATION

INVESTIGATOR SCHNEIDER

TEST SERIES OCB2-673-XXX

FUEL TYPE	TEST NO.	INJECTOR TYPE	MODE	DU (IN)	DF (IN)	L/D	IMP ANGLE (DEG)	PC (PSIA)	NEF	VO (FT/S)	VF (FT/S)	FU (F)	TF (F)	MR	MF/MO	REF	MRVP	PPU (PSIA)	PPF (PSIA)

TABLE B-II (cont.)

HYPERGOLIC STREAM IMPINGEMENT DATA COMPILATION

INVESTIGATOR   SCHMEIDLER

FUEL TYPE	TEST NO.	INJECTOR TYPE		MODE	DO (IN)	DF (IN)	L/D	IMP ANGLE (DEG)	PC (PSIA)	REF	VO (FT/S)	VF (FT/S)	TO (F)	TF (F)	MR	MF/MO	MEP	MXVP	PPU (PSIA)	PPL (PSIA)

TABLE B-II (cont.)

HYPERGOLIC STREAM IMPINGMENT DATA COMPILATION

INVESTIGATOR SCHNEIDER

FUEL TYPE	TEST NO.	INJECTOR TYPE	MODE	DU (IN)	DF (IN)	L/D	IMP ANGLE (DEG)	PC (PSIA)	REF	VO (FT/S)	VF (FT/S)	TU (F)	TF (F)	MH	MF/MU	MEF	MNVP	PPU (PSIA)	PPF (PSIA)

TABLE B-II (cont.)

HYDRAULIC STREAM IMPINGEMENT DATA COMPILATION

INVESTIGATOR SCHNEIDER

TABLE B-II (cont.)

HYPERGOLIC STREAM IMPINGEMENT DATA COMPILATION

INVESTIGATOR   SCHNEIDER

FUEL TYPE	TEST NO.	INJECTOR TYPE		MODE	DU (IN)	DF (IN)	L/O	IMP ANGLE (DEG)	PC (PSIA)	MEF	VO (FT/S)	VF (FT/S)	TU (F)	TF (F)	MH	MF/MU	MEF	MRVP	PPU (PSIA)	PPF (PSIA)
N2H4	161	UNLIKE COMP		MIX	.026	.022	24.	58.	92.	.142+05	67.4	82.4	70.	68.	1.64	.745	2.9	184.1	14.8	2.
N2H4	162	UNLIKE DOUB		MIX	.026	.022	24.	58.	149.	.167+04	33.8	44.4	68.	66.	1.53	.858	1.4	177.9	14.4	2.
N2H4	163	UNLIKE DOUB		MIX	.026	.022	24.	58.	201.	.179+04	45.0	55.2	70.	70.	1.64	.740	2.0	173.1	12.0	2.
N2H4	164	UNLIKE DOUB		MIX	.026	.022	24.	58.	147.	.750+04	33.0	41.7	73.	74.	1.62	.766	1.6	198.0	15.2	2.
N2H4	165	UNLIKE DOUB		MIX	.026	.022	24.	58.	142.	.195+05	41.5	11.9	71.	69.	1.09	.762	0.9	176.0	15.2	2.
N2H4	166	UNLIKE DOUB		MIX	.026	.022	24.	58.	292.	.900+04	37.8	50.9	72.	70.	1.49	.903	2.5	177.0	15.0	2.
N2H4	167	UNLIKE DOUB		R/S	.026	.022	24.	58.	292.	.243+05	79.9	50.9	74.	71.	1.03	.778	3.9	30.2	12.0	1.
N2H4	168	UNLIKE DOUB		SLP	.026	.022	24.	58.	101.	.535+05	127.3	101.9	76.	130.	1.04	.797	15.9	17.	17.2	4.
N2H4	169	UNLIKE DOUB		R/S	.026	.022	24.	58.	79.	.518+05	127.5	165.4	77.	162.	1.01	.803	14.0	20.1	17.2	7.
N2H4	170	UNLIKE DOUB		MIX	.026	.022	24.	58.	63.	.390+05	104.2	132.7	76.	154.	1.03	.782	4.1	23.1	16.2	7.
N2H4	171	UNLIKE DOUB		MIX	.026	.022	24.	58.	70.	.490+05	78.0	99.0	76.	149.	1.09	.782	4.2	22.0	15.2	6.
N2H4	172	UNLIKE DOUB		MIX	.026	.022	24.	58.	164.	.295+05	75.7	96.0	76.	151.	1.09	.773	5.7	21.4	14.1	6.
N2H4	173	UNLIKE DOUB		SLP	.026	.022	24.	58.	205.	.303+05	75.3	97.6	76.	154.	1.61	.804	10.7	20.4	17.2	2.

*INPUT
TEST